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Training of Physicists for Industry—From the Point of View of the Educator

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OUR national welfare demands the wide application of physics for the satisfaction of human needs. Industry is realizing that it must go back of engineering to the parent science, physics. It should be possible in every industry to enjoy results like those which have characterized the communication industry in recent years. There, a phenomenal development has occurred under the leadership of men who have made one of the greatest inventions of all time—the invention of the scientific process of invention as applied to modern industrial problems. This process of invention requires the services in industry of able and well-trained men who work to extend the borders of knowledge wherever this extension may be even remotely concerned with commercial applications. To carry these new ideas and discoveries through to "production," there are also required numerous other workers of widely differing abilities and training.

It is in the larger industries, of course, that this new method of invention has been most successful. The principles involved, however, can be applied even in a small industry. Here, well-trained physicists, familiar with the use of scientific literature, may be employed to apply the results of research to industrial problems and to carry on such work as the resources of the company can support. Moreover, these lesser industries may have fundamental research done in university laboratories by graduate students who hold industrial fellowships.

Why is it not generally realized that physics has much to contribute to industry? In the first place, as I have pointed out elsewhere,[1] much that is physics goes by other names. Physics permeates every branch of industry; yet most persons who deal with its applications are called engineers, and not even "physical engineers." Why did not the goddess of chance bless our subject with a euphonic name and one that does not lead to so much confusion? In chemistry there are *chemists* and *chemical engineers*, and if this paper dealt with chemistry its title could be "Chemical Education." In physics there are *physicists*, but no "physical engineers;" instead, we have electrical, radio, mechanical and aeronautical engineers, and representatives of many other branches of what could properly be called "physical engineering." Yet this appellation cannot be employed, for the same reason that the title of this paper could not be "Physical Education."

The off-springs of physics are so numerous and complex that their parent is likely to be overshadowed. Look up "Chemistry" in the *Encyclopedia Brittanica* and you will find 56 pages. Look up "Physics" and you will find only three. There are, however, references to a large number of lengthy articles in all parts of the encyclopedia that deal with branches and applications of physics, but under entirely different titles. These branches and applications are so important that they naturally have acquired distinctive names.

The importance of physics to industry is not understood, in the second place, because physi-

[1] "The Future of Physics," Univ. of Iowa Studies, No. 33, 1931, pp. 81–86.

cists have held aloof from the applications of their science. This has not been true of chemists. Chemistry had its origin in alchemy; the alchemist wanted gold, and so began the development of chemistry as a means to a practical end. Much of chemistry is still concerned mainly with practical results. Physics, on the other hand, had its origin in philosophy. Until recently it was called "natural philosophy." It attracts the thinker who seeks an *understanding* of nature. The theoretical physicist looks down on the experimental physicist, and even the experimentalist tends toward "purity" and looks down on those who work with *things* for practical purposes.

Archimedes, the founder of mathematical physics, was also a great experimentalist. He applied his physics with extraordinary success to a large variety of important practical problems of peace and war. Yet even Archimedes, who went further in this direction than any predecessor, was a scientific snob. According to Plutarch, "He would not deign to leave behind him any commentary or writing on such subjects; but, repudiating as sordid and ignoble the whole trade of engineering, and every sort of art that lends itself to mere use and profit, he placed his whole affection and ambition in those purer speculations where there can be no reference to the vulgar needs of life."

The aloofness of the physicist has been largely responsible for the gap between the research laboratory and the applications of its discoveries in industry. In turn, physics as a science and a profession has suffered from the lack of the stimulating effects of contacts with industry and the greater popular appreciation and support which it might be enjoying. The present efforts of the American Institute of Physics to bring physicists and industrialists together will thus be of benefit to both groups.

Opinion of Experts Regarding Necessary Training

If physicists are to be successful in industrial work, their training must be planned with a view to the work that they will be called upon to do. Men actively engaged and experienced in such work can help decide what this training should be. Those who planned this program[2] asked a large number of men who have had conspicuous success in applied physics for statements regarding the value of their own training and their opinions as to the best training for industrial work. Thanks to the assistance which has been given so generously by these correspondents, we have available for the first time consistent information from which the following broad outline of a program for the training of physicists for industry has been prepared.

Cultural background. The letters indicate that cultural background should be as rich as time will permit. This means that electives should be included in the curriculum emphasizing particularly economics, history, philosophy and psychology.

Facility in English. All agree that greater facility in written and spoken English should be acquired. One correspondent says:

> "One of the most annoying deficiencies exhibited by the young physicists I have encountered is their inability to put their thoughts on paper. I do not say 'in acceptable form'—but, at all. Apart from all known faults in composition, one finds in their writings astonishing discrepancies between what they say and what they mean. They believe, to paraphrase Alice, that to think while you write is the same as to write *what* you think."

This lack of facility in English is found in students in all fields. Possibly a different type of course, rather than more courses, or some correlation between the work in English and the preparation of reports in other courses would be effective. Certainly, this problem should be given very serious attention.

Foreign languages. There is complete agreement that facility in the reading of both German and French is of the greatest importance, but that a little knowledge of language is of questionable value. Students should study a language long enough to be able to read with ease and then should be required to make use of this reading ability.

Personality factors. The personality of the man in industry was so often mentioned that it is evident that we must consider it in his training.

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[2] Joint Meeting of the Founder Societies of the American Institute of Physics, New York, Oct. 29–31, 1936. The present paper was presented in the Symposium on the Training of Physicists for Industry.

The manager of a large industrial research laboratory writes:

"A man's success in industry depends fully as much upon his personality characteristics as upon his technical and scientific knowledge. A definite effort should be made to determine a student's personality faults, point them out to him, and see, if possible, that these faults are overcome."

Another writes:

"If a man is to succeed in industrial physics, a large measure of his success will be determined by his ability to work with, and to lead, other people."

I do not know what type of courses could possibly secure these results except as by-products. Would they not come more directly from extra-curricular activities? The English can teach us a great deal about the importance of athletics and other leisure-time activities in a student's development.

Importance of the teacher. As teachers, we may well consider the effect of our personal contacts with the student. One man writes:

"While the curriculum is the most tangible factor, it is not the most important. The group of qualities covered by the term 'attitudes' is ever so much more important. These attitudes include scientific honesty, methods of attack on problems, habits of study, and, above all, inspiration and enthusiasm. These qualities probably cannot be taught, except by example. I believe that the most important factor of all is the selection of teachers."

In the correspondence there are many references to particular teachers whose inspiration and guidance was of more value than any particular course. As one man says:

"Courses, as such, do not stand out. The thing that does stand out is the professor, or better, the *teacher* who has given the instruction. To ask me to name the essential element in my education would be synonymous with asking me to name the exceptional men that I had the opportunity to study under from time to time."

If we are to make a success of curriculums emphasizing industrial physics, departmental staffs must include physicists who are as much interested in the applications of physics as the usual staff is in research in pure science. Several correspondents urged that some staff members should be recruited from the industries and that special lectures by successful industrial physicists should be arranged. Undoubtedly good men in sufficient numbers could be attracted from industry to the teaching profession.

Engineering courses. Our correspondents tell us that the physics student who is looking toward an industrial career should take a number of courses in engineering. Those who have not had such courses complain of the lack of them. Those who have had some engineering courses speak highly of them. A few, who have themselves been trained as engineers before going into physics, favor a complete engineering training, followed by graduate study in physics. The vast majority, however, feel that the major emphasis should be upon physics, mathematics, and chemistry, with only such courses in engineering as are necessary to give the engineering viewpoint, some experience in mechanical drawing, and the elements of mechanical and electrical engineering.

One graduate of an engineering school, who is in charge of an important division of a great industrial laboratory, and who has under his direction more than one hundred college graduates, says:

"There is an increasing need for men with four or five years of training who have made physics their major subject. Many of the jobs that in the past have been filled by electrical or mechanical engineering graduates are now better filled by men with more training in science and less in the technological courses. This is probably due to the rapid pace of modern industry. New products are created, developed, placed in manufacture, become obsolete, and are replaced by others at such a rapid rate that a greater proportion of the total engineering effort in present-day industry is of a developmental nature than in the past. The developmental nature of the work requires more basic knowledge than the great majority of engineering graduates have."

Another writes:

"My own training was in physics and I find that my preparation is far more satisfactory than it would have been had I prepared myself as an engineer. It has given me breadth of technical knowledge. While it has been necessary for me to supplement this by some of the practical phases of engineering, I am firmly convinced that this has been more easily accomplished than if I had made the adjustment with a training in engineering without a thorough foundation of fundamentals."

Another writes:

"Early emphasis on the engineering side is definitely a mistake. It is my opinion that it is easier to make an engineer out of a student trained for four years in fundamental mathematics, physics, and chemistry, than it is to make a physicist out of a student who has spent his time taking a college engineering course."

Mathematics. The opinion is that physicists usually take sufficient work in mathematics. The complaint is made that the courses, in many instances, are not satisfactorily taught. For example, one man says:

"I felt that mathematics was a thing apart from physics. Although some effort was made to formulate problems that had some bearing on physics, I never really appreciated the use which could be made of mathematics."

Another writes:

"Some of the work in mathematics should be specifically devoted to training in analyzing *practical* problems, learning to select the important and unimportant factors, setting up differential or other equations, and solving by approximate methods if exact methods fail."

The director of one of our great laboratories says:

"In my college days, mathematics was kept 'pure.' It would have added much to my knowledge and interest if it could have been generously applied to physical problems. It is one thing to solve a neat row of symbols in a mathematical text, and quite another to understand a problem well enough to set up a differential equation, determine constants of integration, and keep one's feet on physical ground through the whole process."

Clearly, we have here a problem that will have to be worked out in cooperation with departments of mathematics[3]—a problem, in fact, that is so clear-cut that it might well receive the attention of a special committee of the American Association of Physics Teachers. It is unfortunate that many departments of mathematics are so little concerned with the applications of their science to physics, for the satisfaction of whose demands most mathematics has been developed. It is somewhat as if we had departments of the Dictionary staffed by men largely ignorant of literature and convinced that their beloved words would be contaminated if strung together for such ignoble and practical purposes as the making of sentences endowed with meaning.

Chemistry. With mathematics, the need is for better mathematics rather than for more. With chemistry it is just the opposite. Chemistry is well taught, but physicists do not study it sufficiently. There is almost unanimous agreement that any physicist looking forward to industrial work should have inorganic, organic, and physical chemistry. A leading industrial physicist says:

"Many chemists have a way of viewing matters which is different from the physicist's way, and which is of value to the physicist. I would include a considerable requirement in chemistry—both theoretical and experimental—enough to make the physicist feel himself to be to some extent a chemist."

Another says:

"Most industrial laboratories do not employ physicists to any large extent. This is partly because most physicists do not know enough chemistry or have enough appreciation of chemical methods to be useful in many industries where they might otherwise be very valuable."

A very practical comment is the following:

"It is most important for industrial physicists *in the smaller companies* to know chemistry. In the larger laboratories, they can work with chemists, but in the smaller companies a research physicist is expected to know *science*. If he does not know chemistry, he may be lost."

Although we cannot pretend to answer completely the question of the proper training in physics, we can go further toward an answer than has ever before been possible, for the pooled opinion of this group of men who are experts in the industrial field must carry weight in reaching a decision.

Classical physics. Industry is more concerned with classical physics and general physics, to employ the two terms used most frequently in the letters, than it is with modern physics. One gets the impression that our correspondents, when they speak of classical physics, have in mind mainly the physics which has already found wide application in industry. The kind of physics that the industries are making use of most extensively at any particular time is usually not the kind that at the moment is receiving the most attention in academic departments. The whole soul of the academic man is in research in physics *as a science*, or else he feels that it should be. With some exceptions, he regards the teaching of elementary and intermediate courses largely as hack work. With the vanity characteristic of all human beings, he wants to make others like himself, and so he is principally interested in turning out embryo research men for academic positions. It is of interest that in Europe there are many professors of technical physics, although the number of physicists engaged in industrial work is smaller than here.

[3] The mathematicians need the cooperation of the physicists. Note the following problem, which appears in a recent textbook on college algebra: "A storage battery (such as is used for the ignition, self-starting, and illuminating systems of an automobile) can be charged from a certain dynamo in 32 hours, or from another dynamo furnishing current of the same voltage but of greater amperage, in 28 hours. In what time can it be charged if current from both dynamos is used simultaneously? (Hint. This may be compared to the filling of a tank into which water is flowing from two pipes of different sizes but at the same pressure from each.)"

The manager of a large laboratory writes:

"I believe that in most physics departments too much emphasis is placed on the newer physics—nuclear, atomic and molecular physics, quantum mechanics, and the like. The majority of the best known physicists are working in these new fields and the student naturally looks up to them for guidance and inspiration. He is, therefore, apt to slight the other branches, such as optics, magnetics, and acoustics. It would be very desirable for the students who contemplate going into industry if these older subjects could be taught with the same enthusiasm and emphasis on the part of the teaching staff."

Again and again the importance of intensive training in the fundamentals of general classical physics is emphasized. One correspondent says:

"Certainly every student sent forth labeled as a 'physicist' should know the fundamental principles of physics forward and backward. All the common concepts should be as familiar to him as the concepts of everyday life. These things are the stock-in-trade of the physicist, and he must be able to reach for what he wants from this stock with his eyes closed."

Laboratory work. Although physics is primarily a laboratory science, one would not think so from the way it is taught. Over and over again the need for more laboratory experience is mentioned. One writer speaks of the "great need for developing some adeptness in experimental procedure," and goes on to say:

"Men trained in chemistry generally have this, but few physicists seem able to carry out the necessary experimental work with the equipment available in a small laboratory."

Another writes:

"I would continue laboratory courses into the student's graduate years and would be as interested in teaching him to design and set up his experimental equipment as in instructing him in the number of significant figures he is entitled to use in his computations. I would familiarize him with instruments but would spend as much time with him on pyrometers and thermocouples as on spectroscopes."

Problem courses. If the student needs more work with his hands, he also needs more practice for his mind. One writer says:

"The student is fortunate whose training includes problem courses, independent reading courses, and much laboratory experience. He should work at successively more difficult problems, and particularly those problems that will force him to search in libraries for the accounts of previous studies in order to observe how each successive worker has improved upon, or extended, the material available to him.

"The graduate years should include a course in advanced general physics, covering much of the same ground as a first course in general physics, but, of course, taking advantage of all that the student has learned in several years of undergraduate and graduate study. Such a course should include problems and can be made a review of the whole of undergraduate and graduate physics. By selecting a small number of difficult problems, requiring a considerable search of the literature, and some experimental work, such a course might even be substituted for the usual time and effort put on a graduate thesis problem. The best training would seem to be general practice in attack on problems of various kinds."

The thesis. Many of the correspondents question the value of the doctor's thesis—and these are the same persons who ask for more problem work and laboratory experience. They believe that the time spent upon the thesis is out of proportion to the value received. One writes:

"Aside from the satisfaction of having obtained as much training in the academic field as possible, I think I might be further ahead had I decided to remain in the industrial field into which I went after receiving the master's degree. In other words, I do not believe that there was any marked value in my thesis work so far as industrial work is concerned."

Another writes:

"The chief value of the thesis, and perhaps the only value, is in general training and as a measure of the resourcefulness and persistency of the student."

If we could secure an expression of opinion from all our correspondents upon this question, it appears that we might find the majority strongly in favor of replacing the thesis with problems requiring for their solution a broad knowledge of physics and work in the library and laboratory. Personally, I cannot agree with this viewpoint, for I consider the thesis a most valuable feature of graduate study. Rather would I like to see creative work in applied physics emphasized to such an extent that theses emphasizing applications of physics and developmental research would be a common thing.

New courses. Besides the graduate course in general physics already mentioned, there have been suggested courses in the "Materials of Industry" and in "Physics in Industry." In the former, the physical and chemical properties of materials would be covered. In the latter, one major industry at a time would be studied to discover how the results of physical research are actually applied. One writer says:

"My experience has emphasized a general lack in physicists of an appreciation of the nature of the materials with which an industrial organization must work. Few physicists seem able to think of electrical insulation except

in terms of 'ideal' materials; they cannot visualize alloy steel as a complex solid solution but only as a perfectly elastic solid. They do not seem to understand either the language of the chemist who develops materials, or that of the engineer or shop man who must use them."

Summer work in industry. Several correspondents stressed the importance of urging, or even requiring, students to secure summer work in an industry. One correspondent feels that such work might take the place of some of the engineering courses, for one of their principal values is to familiarize students with heavy machinery. Inspection trips would serve a similar purpose.

An Ideal Curriculum in Industrial Physics

In outlining the curriculum in Table I, the recommendations of a large number of industrial physicists have been followed. Although these recommendations vary somewhat in detail, it has not been difficult to construct a curriculum that conforms strictly to the spirit of the recommendations, with two exceptions. Social sciences are represented by only one course; there should be one or two more. "Broad cultural background" is almost absent, but it should be noted that English composition and modern languages are strongly emphasized.

The curriculum presented here has been prepared to fit the needs of a student interested in electrical work. No one curriculum can meet the needs of all students. There must be options, for some students will be interested in electricity, some in mechanical applications, others in acoustics, or geophysics, etc. Institutions, if they are wise, will not attempt to emphasize many fields. Within certain limits, however, they should offer alternative courses and a selected list of electives to provide for individual needs and interests. For example, a curriculum for students interested in mechanical applications would include courses in mechanical engineering and a course in hydraulics, and would omit some of the work in electrical engineering. It will be noted that the subjects which are given a somewhat different emphasis from that customary in the training of physicists are: English, German, French, classical (general) physics, chemistry, engineering courses, and laboratory work.

Table I. *An ideal curriculum in engineering physics (electrical option).*

First Year			Second Year		
Course	Sem. hrs. Sem. 1	Sem. hrs. Sem. 2	Course	Sem. hrs. Sem. 1	Sem. hrs. Sem. 2
English composition	3	3	General physics	5	5
College algebra[1]	3	–	Calculus	4	4
Trigonometry[1]	3	–	Heat (with lab.)	–	4
Analytic geometry	–	4	Principles of economics	3	–
General chemistry	5	5	German[3]	4	4
Mechanical drawing[2]	2	2	Physical Education	1	1
Shop[2]	–	2			
Physical education	1	1			
Third Year			**Fourth Year[5]**		
Electricity and magnetism	2	2	Modern physics	3	–
Light (with lab.)	4	–	Acoustics	–	3
Mechanics (with lab.)	4	–	Theory of measurements	–	3
Electrical measurements (lab.)	–	2	Physics in industry	–	2
Physics colloquium[4]	0	0	Physics colloquium	1	1
Organic chemistry	2	–	Differential equations	3	–
Organic chemistry (with lab.)	–	4	Physical chemistry	3	–
Materials of engineering (with lab.)	–	4	Physical chemistry (with lab.)	–	4
Advanced English composition	2	2	D. C. machinery (with lab.)	4	–
Scientific German	3	3	A. C. machinery (with lab.)	–	4
			Scientific French	3	–

Fifth Year[6]		
Course	Sem. hrs. Sem. 1	Sem. hrs. Sem. 2
Mathematical physics[7]	3	3
Gaseous conduction, photoelectricity (with lab.)	4	–
Electron tubes, high frequency phenomena (with lab.)	–	4
Advanced thermodynamics	3	–
Advanced calculus	3	3
Practical problems involving partial differential equations	–	3
Colloquium	1	1
Research for Master's thesis	2	2

Sixth and Seventh Years

Industrial physicists and personnel directors say that industry will be able to absorb a large number of physicists with four and five years of training. Many students will wish to take a sixth year, or to complete the work for the Ph.D. These last two years will vary widely according to the interests of the student and the facilities of the department. Suffice it to say that theses in technical physics should be encouraged and that familiarity with many branches of physics, rather than too great specialization, should be emphasized. Except in rare instances, a man cannot be trained specifically for the work that he will do later.

[1] If the student has had college algebra and (or) trigonometry, he should proceed with German or French.

[2] If the student has had this work, substitute courses in the social sciences.

[3] It is assumed here that the student had two years of secondary school French, and no German.

[4] During the junior year the student should be expected to attend the Colloquium or "Journal Club" regularly. He should participate if he wishes.

[5] At the end of the fourth year the student receives the degree of Bachelor of Science in Engineering Physics.

[6] At the end of the fifth year the student receives the degree of Master of Science in Engineering Physics.

[7] A problem and review course in which the student acquires practice in the methods of the various branches of classical mathematical physics. Vector methods should be used where applicable.

Existing Curriculums

Many will be surprised to learn that the general idea of a planned curriculum of the sort demanded is not new. About fifteen years ago half a dozen physics departments realized the need for such curriculums and organized them under the title, "Engineering Physics." All are

administered in the college of engineering, whether or not the department of physics happens to fall in liberal arts or engineering in the general plan of organization. These institutions are the University of Illinois (1917), McGill University (1920), Montana State College (1922), Lehigh University (1924), Ohio State University (1924), and the University of Oklahoma (1924). In 1934 the University of Toronto adopted such a program. Somewhat similar programs, but without the distinctive label, and varying greatly among themselves, are in effect at a number of other institutions of which the California Institute of Technology, the Carnegie Institute of Technology, the University of Denver, Massachusetts Institute of Technology, the University of Michigan, Pennsylvania State College, the University of Pittsburgh, and Rensselaer Polytechnic Institute furnish typical examples. Applied physics, without any especially outlined programs, has been given attention at Cornell University, Union College, and a few other institutions.

The curriculums of these institutions vary widely but many of them approximate the one in Table I. An expression of opinion concerning the value of this training from some of the comparatively young men who followed these curriculums should therefore be significant. More than sixty-five letters were received from such men. Where they express satisfaction with their training, one finds that it corresponds with the curriculum outlined in Table I. Where there is dissatisfaction, their training does not meet this standard. One finds exactly the same emphasis upon the need for English, German, French, and better taught mathematics. In many instances these graduates studied more chemistry than the older generation and all took more courses in engineering. They are correspondingly better satisfied with their training.

Practically all the courses called for in Table I are available in any university. Except in the institutions that have been mentioned, however, there is little encouragement for a student to secure such a program. This is a reflection of the evil of excessive departmentalization—one of the greatest evils of American education. Because of a selfish desire to keep students in their own departments and ignorance of the importance of work in related fields, faculty members are wont to herd students into narrow vertical structures, instead of urging them to build broad foundations upon which their own personal careers can be set at any one of several places and can be well braced from different sides, if necessary. If you should read these letters, or if you should talk with students about these problems, as I have, you would come inevitably to the conclusion that carefully planned curriculums of this general type, which cut across departmental and college boundaries, are the most practical means of breaking down these barriers.

We cannot trust to luck that students will have the information and foresight with which to plan wisely. Unless curriculums of this sort are adopted, physics departments will continue in their conservative ways and students whose interests should place them in applied physics will continue to seek the engineering college. The secondary school student knows nothing about applied physics as a career. Dr. Herbert E. Ives hit the nail on the head when he said, "The kind of mind that leads a man to choose engineering is the kind we need in applied physics."[4]

For the curriculum to be administered by the department of physics, but within the framework of the engineering college, where one exists, is an essential part of the plan. If applied physics is recognized as one of the major fields in the engineering college, students consider it along with civil, mechanical, and electrical engineering when they choose a major in the sophomore year. Thus they have an opportunity to make a more rational decision. If curriculums are not planned so that this is possible, the student must solve such problems for himself. Even when he is fortunate enough to reach the right decisions, it may be so late that much back-tracking and side-stepping will be required. Moreover, among students there is a clannish tendency and a desire to conform. It is not easy for a boy who has started in engineering to leave his fellows and change to liberal arts. It is much easier to change from liberal arts to engineering, for liberal arts is a vague classification and a boy

[4] Herbert E. Ives, "Some Aspects of Research in Applied Physics," J. Engr. Ed. **22**, 82 (1931).

interested in applied physics will probably be happier classified as an engineer.

Initiation of Curriculums

There are three types of institutions in which curriculums directed toward industrial and applied physics should be worked out. First, there is the large university with a well-developed physics department, college of engineering, and graduate college; here a curriculum within the engineering college can easily be arranged. Second, there are the separate engineering colleges and the colleges of the A. and M. type, in which the physics department sometimes occupies a subsidiary position as a service department. In such colleges the main obstacle may be that many engineers lack an understanding of the importance of physics; here physics must insist on its rightful place as one of the possible major subjects. Third, there is the liberal arts college that is not associated with an engineering college. It appears at first that there might be insurmountable obstacles here. Instead, this affords a rare opportunity, for at such a college the engineering-minded student finds his way at once to the physics department. There is no problem of proper placement. The necessary courses in languages, mathematics, and chemistry are available. All that is lacking are the engineering courses. This deficiency can be removed by having the physics department give a few courses in the fundamentals of engineering. If sufficient laboratory facilities are not available, summer work in industry should be required.

The chief difficulty in developing programs of this kind will not be with problems of administrative organization or with the opposition of a conservative engineering faculty, but with physicists themselves. There are some departments that do not wish to be bothered with the engineering type of mind. These departments fail to recognize the right of industry to have physicists trained for its service and of students to secure this training. There are other departments that feel that the needs of industry for physicists with five or six years of training can be met with men who strive for the Ph.D. and fail—not realizing that industry wants no second raters but, instead, those first raters who are by temperament and ability fitted for work in industrial physics.

Those who are interested in the broader significance of the educational program may feel that colleges and universities should hesitate to devote themselves to training men for what may turn out to be anti-social activities. At a time when the men who are heralded as the great leaders in industrial development make a god of the principle of obsolescence and use their science to make things wear out as fast as they can, rather than to make things as good and as lasting as they can, we have a right to be frightened at the possible consequences of putting more science at their disposal. It is not within the province of this paper to do more than suggest that there are these larger problems. We should know, for example, what industry is going to do toward satisfying as fully as possible the needs of the people at large instead of directing its efforts chiefly toward profit for the few. Scientists and engineers must be concerned with these problems as citizens, as well as professionally. As citizens, we must help set up the social controls that the last few years have shown are necessary if our professional work is not to destroy us. Today, somewhat blindly, and with more hope than certainty, we must have faith that it will redound to the welfare of coming generations if we help develop industry to the highest peak.

In this paper the importance of applied physics has been emphasized but with no intention of implying that it is more essential to our national welfare than is research in pure physics. As Heisenberg[5] says in a recent book: "It is the task of pure science to make tillable the soil upon which technology is to grow." Our colleges and universities should be devoted to creative work, but creative work in physics is not limited to research in pure science. There can also be creative work in applied physics and in the teaching of physics. Unless there is a peculiar and legitimate reason for an unbalanced program, all three phases must be adequately represented if a department of physics is to fulfill its obligations to the profession of physics, to students of physics, and to society.

[5] *Wardlungen in der Grundlagen der Naturwissenschaft* (S. Herzel, 1936).

Plane and Solid Angles

Their Pedagogic Value When Introduced Explicitly

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PROBABLY most teachers of physics make use at one time or another of a method of handling units which seems to have been first suggested by A. Lodge[1] in 1888. D. L. Webster[2] elaborated it further and P. W. Bridgman[3] has discussed certain aspects of it critically, characterizing it as "the simplest and most reliable way of changing units with which I am acquainted." The method referred to has no accepted name but consists in substituting units along with numerical values when solving a physical equation for a particular case and thereafter treating the symbols for the units as algebraic quantities, eventually reducing the whole collection, by appropriate substitutions and cancellations, to the unit in which it is desired to express the result. As Bridgman[3] indicates, the method amounts to writing, in parallel with the numerical values, a dimensional formula in which the dimensional symbols are the names of concrete units rather than the (M), (L) and (T) of the classical analysis. If used consistently and regularly the method has great pedagogic merit, for the student may be given just one set of algebraic equations which he can be taught to look upon as shorthand statements of physical laws or as definitions of physical quantities that are valid no matter in what units one may choose to express any of the quantities involved. Each letter in an equation is to be thought of as representing not merely a number but the numerical value of a physical quantity *together with the unit in which it is expressed*. This set of algebraic equations contains no numerical coefficients except an occasional shape factor like the $\frac{1}{2}$ in K.E. $=\frac{1}{2}mv^2$; all other numerical relations are relegated to corresponding *equations between units*, where they properly belong.

For instance, Newton's second law may be written thus:

$$F/a=F'/a'=W/g=m=\text{a constant}$$

called the *mass* of the body in question. Corresponding equations defining units of force are:[4]

$$1\text{ dyne}=1\text{ gm(mass)}\cdot\text{cm/sec}^2,$$
$$1\text{ poundal}=1\text{ lb(mass)}\cdot\text{ft/sec}^2,$$
$$1\text{ gr(force)}=1\text{ gm}\cdot 980.7\text{ cm/sec}^2=980.7\text{ dynes},$$
$$1\text{ pd(force)}=1\text{ lb}\cdot 32.18\text{ ft/sec}^2=32.18\text{ poundals}.$$

As stated previously, none of the general algebraic equations should contain any constants, either overt or concealed, that restrict their validity to the use of particular units or a particular system of units. It is because of failure to meet this requirement that the method usually breaks down whenever angles are involved and the first purpose of this paper is to point out how this breakdown may be avoided.

To illustrate the type of difficulty encountered, let us find the acceleration of a particle moving in a circular path of 5 cm radius with a constant speed of 200 rev/min. Following the method as usually applied, we have

$$a=r\omega^2=5\text{ cm}\cdot 200^2(\text{rev/min})^2\cdot 1\text{ min}^2/3600\text{ sec}^2$$
$$=55.6\ (\text{cm/sec}^2)\cdot\text{rev}^2.$$

Now one expects an acceleration to be expressible in such a combination of units as "cm/sec^2" so that the "rev^2" in the foregoing result is evidently redundant. And even if one realizes that the equation $a=r\omega^2$ is restricted for its validity to the use of the radian as the unit of angle and therefore converts the "rev^2" into "$4\pi^2$ rad^2," thus getting

$$a=55.6\ (\text{cm/sec}^2)\cdot 4\pi^2\text{ rad}^2=2200\ (\text{cm/sec}^2)\cdot\text{rad}^2,$$

this still leaves a meaningless angular unit in the result. Webster[2] pointed out that this sort of difficulty has its root in our own inconsistency in

* With regret we note the death of Professor Brinsmade, which occurred a few days after this paper was accepted for publication.—The Editor.

[1] Nature **38**, 281 (1888).

[2] Science (N.S.) **46**, 187 (1917). See also Webster, Farwell and Drew, *General Physics for Colleges* (Century, 1923, 1926). Fairly consistent use of the method in recent texts is to be found in Hausmann and Slack, *Physics* (Van Nostrand, 1935) and in Hobbie, *Introduction to College Physics* (Farrar and Rinehart, 1936).

[3] *Dimensional Analysis* (Yale Univ. Press, 1922), Chap. III.

[4] It is very helpful to the student to make some such distinction in symbols as that used here, namely, "gm" and "lb" for the gram and the pound as units of *mass*, and "gr" and "pd" for the gravitational units of *force*.

saying that we define *angle* by the equation $\theta = s/r$ but, actually, using many units of angle which are inconsistent with this definition. His remedy is to "insert or rub out the unit radian whenever it is convenient to do so" on the ground that the radian is a pure number and therefore dimensionless. But this rule sometimes leads to disaster as in the following: to find the frequency of a note whose wave-length in air is 15.3 in., given that the speed of sound in air at the existing temperature is 343 *m*/sec, where we have

$$\nu = v/\lambda = [(343 \text{ m/sec})/(15.3 \text{ in.})]\cdot 39.37 \text{ in./m} = 882/\text{sec} = 882 \text{ rad/sec}.$$

Here the reader will probably object that the use of the term *frequency* involves the implication that it is to be expressed in vibrations—or cycles, not in radians per unit of time. But, for the student, this is just the sort of implied restriction that tends not only to destroy the value of this whole method but also to obscure such important matters as the fundamental identity of the concepts of frequency and angular speed. We shall return shortly to this matter of frequency, wave-length, etc.

The writer has for some years been overcoming this whole difficulty by the seemingly obvious means of writing the defining equation for *angle* as $\theta = k(s/r)$, where $k = 1 \text{ rad} = (1/2\pi) \text{ rev} = (1/2\pi)$ cycle $= (360/2\pi)$deg, etc. Since k is used so often as a general symbol for proportionality constants, it is somewhat better to write

$$\theta = (s/r) \text{ rad}, \tag{1}$$

and then to replace the 'rad' by any other of its equivalents if and when needed. Eq. (1) rather than the usual definition must then be used consistently in the derivation of any equations that contain, either explicitly or implicitly, an angle expressed as a ratio of arc to radius. To be sure, this amounts to the introduction of a unit of angle as a fourth primary dimension; but Bridgman[5] has effectively exploded the earlier trinitarian doctrine regarding primary dimensions and R. T. Birge[6] has still further emphasized the arbitrary character of our choice of them, so that there seems to be no logical fallacy in this procedure and its adoption is to be justified simply by its pedagogic expediency. Mention should be made here of a somewhat similar suggestion put forward by W. W. Williams[7] who splits the usual dimension (L) into three mutually perpendicular dimensions (X), (Y) and (Z), and writes the dimensions of angle as $(X\cdot Y^{-1})$.

A list of algebraic equations and some corresponding unit relations as they appear when derived in this way is given in Table I.

The torque equation given here may strike some readers unpleasantly as an introductory definition but it appears to be the logical one to use in this purely algebraic treatment. It may be of interest to note that this does away with the usual dimensional identity of torque and energy. The "rad" here serves the further purpose of caring for the necessary distinction between what we usually call vector and scalar products.

The application of this treatment of angles to periodic motion and wave phenomena calls for certain revisions in the usual methods of presenting these subjects. The concept *frequency* is really only partially applicable to types of periodically recurring motion other than simple harmonic. Even the common elementary textbook definition of frequency as "The number of vibrations executed in a unit of time" cannot be applied accurately to motions other than simple harmonic if fractions of a vibration are involved and the term is almost never used except in connection with phenomena that are at least very nearly sinusoidal.

One way of specifying the uniqueness of simple harmonic motion among all possible types of periodic motion is to say that if we put all positions of the motion into one-to-one correspondence with so-called "phase angles," there being 360° or 2π rad or 1 cycle of phase angle associated with each complete vibration, the actual motion corresponds to a *constant* time-rate of change of phase angle. Another way of putting it is to say that s.h.m. is the type that has only *a single frequency*, applicable to all phases of the motion, this being the same as the constant angular speed of the associated phase angle. From this viewpoint, *angular speed* (of phase

[5] Reference 3, Chap. V.

[6] Am. Phys. Teacher **3**, 102, 171 (1935). The writer is indebted to Dr. Birge for an opportunity to see the latter paper in proof and for some very helpful correspondence.

[7] Phil. Mag. (5) **34**, 234 (1892).

TABLE I. *List of algebraic equations and some corresponding unit relations.*

Algebraic Equations		Unit Relations
Angular speed	$\omega=\frac{\theta}{t}=\frac{s/r}{t}\text{ rad}=\frac{v}{r}\text{ rad}$	$1\ \frac{\text{rev}}{\text{sec}}=2\pi\ \frac{\text{rad}}{\text{sec}}$
Centripetal acceleration	$a=\frac{v^2}{r}=\frac{(r\omega/\text{rad})^2}{r}=\frac{r\omega^2}{\text{rad}^2}$	$1\ \frac{\text{cm}\cdot\text{rad}^2/\text{sec}^2}{\text{rad}^2}=1\ \frac{\text{cm}}{\text{sec}^2}$
Angular acceleration	$\alpha=\frac{\omega_2-\omega_1}{t}=\frac{v_2-v_1}{rt}\text{ rad}=\frac{a}{r}\text{ rad}$	$1\ \frac{\text{cm/sec}^2}{\text{cm}}\text{ rad}=1\ \frac{\text{rad}}{\text{sec}^2}$
Torque	$\mathrm{T}=\frac{\text{Work}}{\text{Angle}}=\frac{Fs}{\theta}=\frac{Fs}{(s/r)\text{ rad}}=\frac{Fr}{\text{rad}}$	1 dyne·cm/rad = 1 erg/rad
Moment of inertia (of particle)	$I=\frac{\mathrm{T}}{\alpha}=\frac{Fr}{\text{rad}}\cdot\frac{r}{a\text{ rad}}=\frac{(F/a)r^2}{\text{rad}^2}=\frac{mr^2}{\text{rad}^2}$	$1\ \text{gm}\cdot\text{cm}^2/\text{rad}^2$
Rotational K.E.	$=I\omega^2/2$	$1\ (\text{gm}\cdot\text{cm}^2/\text{rad}^2)\cdot(\text{rad}^2/\text{sec}^2)$ $=1\ \text{gm}\cdot\text{cm}^2/\text{sec}^2=1\text{ erg}$
Work to produce rotation	$=\mathrm{T}\theta$	1 (erg/rad)·rad = 1 erg
Angular momentum	$=I\omega$	$1\ \frac{\text{gm}\cdot\text{cm}^2}{\text{rad}^2}\cdot\frac{\text{rad}}{\text{sec}}\cdot\frac{\text{sec}}{\text{sec}}=1\ \frac{\text{gm}\cdot\text{cm}^2}{\text{sec}^2}\cdot\frac{\text{sec}}{\text{rad}}$ $=1\text{ erg}\cdot\text{sec/rad}=2\pi\text{ erg}\cdot\text{sec/cycle}$
Angular impulse	$=\mathrm{T}t$	1 (erg/rad)·sec = 1 erg·sec/rad.

angles) and *frequency* represent fundamentally identical concepts, except for the rather unfortunate conventional implication regarding units previously mentioned. In the experience of the writer, it is much more enlightening to define frequency as *the ratio of the phase angle covered to the time elapsed* than to use the common definition. Frequency is not "a number of vibrations" any more than linear speed is "a distance," whether covered in one second or in any other unit of time. Both speed and frequency are time-rates-of-change, the one of position and the other of phase angle, and might better be openly presented as such.

If we define frequency in the way suggested here, then *period*, the reciprocal of frequency, will be defined as *the ratio of the time elapsed to the phase angle covered*. In other words, we shall not think of a period as being simply a length of time any more than we think of speed as being simply a distance.

In the same way the idea of phase angle is really inherent in the concepts of *wave-length* and *wave number*. The former, from this viewpoint, should be defined as *the ratio of the distance between any two points in a wave train to the phase difference between the two points;* it could equally well be measured in "cm/deg" or in "cm/rad" as in the customary "cm/cycle." If in the second problem worked out above, the value of λ had been given as 15.3 in./cycle and so inserted into the equation, the result would have come out automatically as 882 cycles/sec and the method would have worked perfectly. Wave-number is simply the reciprocal of wave-length and is expressible in terms of the "cycle/cm," "rad/cm," "deg/cm," etc.

Some objection to this may arise in the reader's mind especially in connection with determinations of the length of the meter in terms of wave-lengths of light. From our point of view the standard meter should be reported as

"1,553,164.24 wave-length·*cycles* of red cadmium light . . . ." Operationally, all determinations of wave-lengths of light consist in the measurement of distances between points identified by their relation to an optical fringe system of some sort. This fringe system is formed because of variations, from point to point of the optical field, in the phase differences between the light coming from two or more virtual sources, each whole fringe indicating a variation of a whole cycle. The wave-length is computed as the ratio of the measured distance to the observed phase variation, multiplied by a dimensionless shape factor which depends on the geometry of the apparatus. For instance, in a Michelson interferometer we have the relation $\lambda = 2d/n$, where d is the distance traveled by the movable mirror and n is the change in phase difference between the two interfering beams which is produced by the motion. Merely because n is usually spoken of as "the number of fringes passed over," we should not allow ourselves or our students to be blinded to the role of the fringe system in the logical structure of wave theory. Again, in the use of a grating, the distance measured is that between, say, the zero and the first, second, third, etc., -order image of the spectral line in question. The images identify for us points where the phase differences between the light from successive grating elements is (very exactly) zero, one, two, three, etc., *cycles* and the computation of λ always necessitates division of the measured distance by the difference in spectral order of the end points.

Applying these ideas to quantum theory, expressed in such equations as $E = h\nu$ or $\lambda = h/mv$, we find that the Planck constant must be taken to be equal to 6.55×10^{-27} erg·sec/*cycle*. This helps to emphasize the Bohr and Heisenberg interpretation of h as the connecting link between discontinuous or particle-like modes of description and continuous or wave-like modes, rather than the early interpretation of it as a natural unit of *action*. Also if h is to be taken as symbolizing any sort of fundamental discreteness in nature, this formulation points to *angular momentum* as the quantity to be thought of as taking on only discrete values.

Table II contains a few elementary equations as they appear with these ideas embodied in them.

In a mechanically oscillating system,

$$\text{Frequency} = (1/2\pi)(f/m)^{\frac{1}{2}}\ \text{cycle} = (f/m)^{\frac{1}{2}}\ \text{rad}$$
$$\text{Period} = 2\pi \cdot (m/f)^{\frac{1}{2}}/\text{cycle} = (m/f)^{\frac{1}{2}}/\text{rad}.$$

In applying the method where trigonometry is involved, it is not necessary to treat the trigonometric functions as anything but pure numbers since no one ever measures them in any way other than as ratios of two distances each expressed in the same unit. But differentials of these functions as ordinarily expressed are valid only when the angles themselves are expressed in radians. So, to apply the method successfully where such differentials are involved, it is necessary to state this fact explicitly just as we did in defining angle as a function of arc and radius in Eq. (1). The same is true of series expansions and of exponential representations. Thus,

$$d(\sin\theta) = \cos\theta d\theta/\text{rad}, \qquad \int \sin\theta d\theta = -\cos\theta\ \text{rad},$$
$$\sin\theta = \theta/\text{rad} - \theta^3/(3!\ \text{rad}^3) + \theta^5/(5!\ \text{rad}^5) - \cdots,$$
$$\sin\theta = (e^{j\theta/\text{rad}} - e^{-j\theta/\text{rad}})/2j.$$

So, by the simple device of always consistently basing any equations involving angles on Eq. (1) instead of on the usual defining equation for angle, we can round out the Lodge-Webster scheme into a completely consistent, pedagogic method not merely for mechanics and heat but for sound and most of light also. At the same

TABLE II. *Illustrative equations.*

Frequency	$\nu = d\theta/dt$	1 cycle/sec $= 2\pi$ rad/sec
Period	$1/\nu = dt/d\theta$	1 sec/cycle $= (1/2\pi)$ sec/rad
Wave-length	$\lambda = ds/d\theta = (ds/dt)/(d\theta/dt) = v/\nu$	1 cm/cycle $= (1/2\pi)$ cm/rad
Wave-length	$\lambda = ds/d\theta = \dfrac{ds/dt}{d\theta/dt} = \dfrac{v}{\nu}$	1 cm/cycle $= (1/2\pi)$ cm/rad
Wave-number	$1/\lambda = d\theta/ds = \nu/v$	1 cycle/cm $= 2\pi$ rad/cm.

time we can illuminate some dark corners of these subjects that have usually been a bit spooky to our students.

To extend the scheme so as to cover with equal completeness the fields of photometry, electricity and magnetism it appears that we must make explicit use of the concept of *solid angle* also. Analogously with Eq. (1) we may define the solid angle subtended at the center of a sphere of radius r by a portion of the spherical surface of area A as

$$\Omega = (A/r^2) \text{ steradian.} \qquad (2)$$

The *luminous flux* Φ_λ emitted through the solid angle Ω by a point source of *source intensity* I is given by $\Phi_\lambda = I \cdot \Omega$ and the commonly employed unit, the *lumen*, is defined as 1 lumen $=1$ candle·steradian (although not usually in just these words). Also, *intensity of illumination* is defined as $\text{Ill} = \Phi_\lambda/A$, or $= d\Phi_\lambda/dA$, with the customary units the "lumen/ft²" and the "lumen/m²." If the illumination considered is from a single point source and if the illuminated surface is so oriented as to receive the light normally, we have

$$\text{Ill} = \frac{d\Phi_\lambda}{dA} = \frac{Id\Omega}{dA} = \frac{IdA \text{ sterad}}{r^2 dA} = \frac{I \text{ sterad}}{r^2}, \qquad (3)$$

which may be taken as the basic equation of photometry. From the foregoing derivation one sees plainly that the "inverse square" part of it is simply a matter of geometry and that the so-called "foot-candle" and "meter-candle" are really 1 candle·sterad/ft² and 1 candle·sterad/m², respectively; that is, simply other names for the "lumen/ft" and the "lumen/m²."

If we bring the *solid angle* idea out into the open by this sort of presentation, all the usual student difficulties and obscurities such as the meanings of *spherical candlepower* and *beam candlepower* and the distinction between *intensity of illumination* and *surface brilliancy*, dI/dA, become simple and understandable.

Similar considerations apply to the concept of solid angle as it occurs in electromagnetic theory, since *electric flux* and *charge* are related to each other in exactly the same way as are *luminous flux* and *source intensity*. The explicit expression of this fact clarifies Gauss' theorem for electrostatics as well as making it obvious that Heaviside's "rationalization" of units consists fundamentally in the implicit adoption of the complete solid angle or *steregon* (4π steradians) as the unit of solid angle instead of the steradian.

Not many people even now seem to realize this latter fact or the further related one that the word "turn" in the electrical engineering unit the *ampere·turn* is simply another name for the steregon. The *magnetomotiveforce*, M.M.F., set up by a *current* i is given by the product $i\,\Omega$ of the current and the amount of interlinkage between the electric and magnetic circuits (i.e., the solid angle Ω swept out by the magnetic circuit as viewed from a point that moves completely around the electric circuit); but this idea tends to be obscured by the practice of treating solid angles as necessarily dimensionless. If, however, one boldly introduces the "steradian" or the "turn" as an additional primary dimension when developing electromagnetic theory, the whole subject loses much of its apparently arbitrary character and all equations may be set up in such form as to be valid for any of the customary units that one pleases to use, provided that one always introduces symbols for the units along with numerical values. For instance, from classical magnetostatics we have the general relation, M.M.F. = Work/Pole-strength, with the corresponding defining equation for the absolute unit, 1 gilbert = 1 erg/U.P.; and corresponding to the general relation M.M.F. $= i\,\Omega$, we have the defining equation for the absolute unit of current, 1 abamp = 1 gilbert/sterad, without any reference to idealized tangent galvanometers or other such apparently arbitrary and special apparatus. From this mode of approach we can see very directly that 1 amp·turn $=(1/10)$abamp·4π sterad $=(4\pi/10)$ gilbert, a relation whose origin is often none too clear.

This explicit introduction of the solid angle concept thus makes it possible to extend the Lodge-Webster scheme to photometry, electricity and magnetism. The writer has been doing this for several years in a course in electricity and magnetism for juniors and has found it very successful.

THE most brilliant discoveries in theoretical physics are not discoveries of new laws, but of terms in which the law can be discovered.
—MICHAEL ROBERTS AND E. R. THOMAS, *Newton and the Origin of Colors.*

Professor James Beebee Brinsmade
1884–1936

JAMES BEEBEE BRINSMADE, professor of physics and chairman of the department at Williams College, met a distressingly sudden death on September 13, 1936. Though he had been in poor health for the past four years his teaching work of the last semester had been carried with enthusiasm and vigor and the vacation rest at his summer home in Nantucket had apparently given him renewed strength. On his way to Williamstown, prepared, as he supposed, to plunge into the active work of the coming college year, he broke the journey by an overnight stop in New Bedford and in the morning of September 13 was found lifeless in his bed at the hotel, having died from an attack of coronary thrombosis.

Brinsmade was born on May 12, 1884, the son of Henry Newman Brinsmade, a mining engineer of New York. His early education was obtained at the Brooklyn Latin School and the Hotchkiss School. He received his A.B. degree from Yale College in 1906. In 1911, having decided upon a career as a teacher of physics, he entered the graduate school of Harvard University and here received the A.M. degree in 1913 and the Ph.D. degree in 1917. Beginning his teaching work, in 1913, as an assistant in physics he was appointed to an instructorship at Harvard in 1917. In the year 1918–19 he served as first lieutenant in the United States Army Signal Corps (Air Service). In 1919 he was called to Williams as an instructor in physics, was made assistant professor in 1920, associate professor in 1928, and professor in 1932.

Brinsmade's early researches, at Harvard, were in the field of infrared absorption bands. In 1926–27 he spent a sabbatical year in Pasadena as visiting research fellow of the California Institute of Technology, where he conducted noteworthy researches on electron reflection. Endowed with a natural aptitude for experimentation and a keenly analytical mind he was well equipped for research work. But it was the teaching of physics that appealed most strongly to his interest. His teaching was characterized by soundness and thoroughness that would not tolerate looseness of statement or slipshod methods of reasoning. He took delight in formulating exact and rigorous presentations and was particularly insistent on the correct inclusion of units in every physical equation. He was particularly interested in the theory of magnetism and electricity and had given much study to methods of presenting this subject to undergraduates. His extensive notes, accumulated over a period of years of teaching experience in this field, show much originality.

In his dealings with his students he was a model of courtesy and willing helpfulness, sparing neither time nor pains in his efforts to clear up their difficulties and spur their interest in the work. His counsel and encouragement were often sought and freely given. And for colleagues no less than for pupils his strong but ever kindly personality carried a charm that none could fail to recognize.

He is survived by his widow, Margery Hickox Brinsmade.

—W. E. McElfresh

A. A. P. T. Award for Notable Contributions to Teaching

THE American Association of Physics Teachers committee appointed to make the annual award for notable contributions to the practice and art of physics teaching made final arrangements for the first award at a meeting held in New York City on October 29. The award for this year will be announced at the joint banquet of the Association and the American Physical Society to be held at the Chalfonte Hotel, Atlantic City, on December 29. The annual medal and certificate from the Association have been made possible for the next three years through the generosity of an anonymous donor. The committee on awards consists of the president of the Association, the secretary, the last two past-presidents, and the editor of *The American Physics Teacher*.

The Early History and the Methods of Infrared Spectroscopy

R. Bowling Barnes* and Lyman G. Bonner,** *Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

The advances of experimental physics during the past few years, particularly the discoveries of the Raman effect and the hydrogen isotope of mass 2, together with the vast improvements in theoretical interpretation of polyatomic molecules, have furnished the impetus for corresponding developments in the field of infrared spectroscopy. Within the last twenty years, in fact, experimental infrared has advanced from the status of a series of neat experiments to a definite place as an important branch of spectroscopy and a most powerful tool for the investigation of the structure of molecules.

This paper is intended both for the general reader and for the student who has only recently become interested in the infrared. Reference cannot be made here to every investigation that has a bearing upon the subject; only those are mentioned that seem best to illustrate the points in question. For more complete bibliographies one should refer to the recent treatises and articles in this field.[1]

Historical Review

In 1800 Wilhelm Herschel performed experiments that aided greatly in clarifying and advancing the study of spectra, and that at the same time marked the discovery of the infrared. He placed the bulb of a sensitive thermometer in the various regions of a solar spectrum and observed the rise in temperature of this thermometer with respect to a similar one that was kept out of the spectrum. His results indicated a rise of 2° in the violet, 3.5° in the green, and 7° in the red, thus showing that radiant energy was present in all parts of the visible spectrum. He next proceeded to estimate the relative brightnesses of the various parts of the spectrum and found a decided maximum in the green and yellow. The fact that the distribution curves for the heat and light did not agree disturbed him, and led him to search for the maximum of the heat curve. In a second publication Herschel announced that this maximum was out beyond the red end of the spectrum. With a visible spectrum 4 in. long, he found a maximum of 9° rise in temperature 1.5 in. beyond the red end and no appreciable rise at all beyond the violet end[2] (Fig. 1).

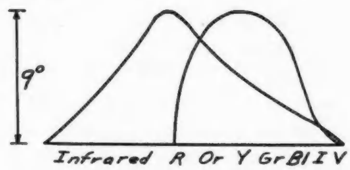

Fig. 1. Herschel's comparison of the distribution of light and heat in the sun's spectrum. The vertical scale of the latter curve is chosen to make the two maximums the same height. A glass prism was used.

Immediately there followed a long series of investigations to determine whether these invisible infrared, or "heat," rays and visible light were the same, or whether they represented different phenomena. It was easily discovered that both followed exactly the same laws of refraction and reflection. Herschel demonstrated that although the infrared rays were refracted according to Snell's law, they were refracted much less by a given lens than was visible light. The transmissions of various substances for infrared and visible radiation were then studied and found to be greatly different, some materials being opaque to light and at the same time transparent to the infrared, and *vice versa*. Because of this, and because of their different distribution curves, Herschel remained firmly convinced that the invisible rays and light were fundamentally different. Later studies of the dependence of the emission upon the temperature of the source and studies of the selective ab-

* Now with the American Cyanamid Company.
** National Research Fellow.
[1] Rawlins and Taylor, *Infrared Analysis of Molecular Structure* (1929); Schaeffer and Matossi, *Das Ultrarote Spektrum* (1930); Lecompte, *Le Spectre Infrarouge* (1928); Dennison, Rev. Mod. Phys. **3**, 280 (1931); Eucken-Wolf, *Hand- und Jahrbuch der Chemischen Physik* (1934), Vol. 9–II.

[2] In 1801, J. W. Ritter (Gilbert's Ann. **7**, 527 (1801); **12**, 409 (1803)), found that the photographic action of light on silver chloride extended beyond the violet end of the spectrum. He verified the existence of the infrared rays reported by Herschel, and noted that they greatly retarded the photochemical action of light.

sorption of various materials made it clear that these visible and invisible rays were identical in character.

Throughout the next half-century the history of spectroscopy is intimately associated with the names of Young, Wollaston, Fraunhofer, Brewster, J. F. W. Herschel, the son of the discoverer of the infrared, Helmholtz, Talbot, and Kirchhoff. During this period many a heated argument was held regarding the discovery and interpretation of the Fraunhofer lines, and the possibility of identifying a substance by means of the spectrum which it emitted. In passing, it is interesting to note that the understanding of this latter possibility was delayed some 30 to 40 years by the fact that sodium is found in minute quantities almost everywhere—the yellow *D* lines were observed in every flame and in every other source of light. Had it not been for this puzzling fact, Herschel and not Kirchhoff might today be looked upon as the real founder of spectroscopy.

Introduction of the thermopile

The next chapter in this history must certainly begin with mention of the discovery of thermoelectricity by Seebeck in 1823 and its subsequent use by Becquerel in temperature measurements. Nobili soon afterwards constructed a thermopile and used it successfully with his sensitive astatic galvanometer to measure very small differences of temperature, but it was in the hands of Melloni, later on, that this instrument was developed to its fullest value. Using thin wires of bismuth and antimony, he constructed a thermopile of many junctions and achieved with it a sensitivity over ten times that of his best thermometer. For a period of 22 years he was busy with this new instrument and carried out many infrared investigations. He showed definitely that the position of the energy-maximum in the sun's spectrum was determined by the particular prism used, and explained this fact correctly as being due to the selective absorption of the prism material. He was able also to show that the infrared rays were not homogeneous but consisted of many different rays, analogous to the manner in which white light had been shown to be made up of various colors. He spoke of the "colors" of the infrared rays and after finding that different bodies behaved towards the transmission of these rays just as transparent colored and colorless materials behaved towards visible light, spoke of the "heat color" of a material. Rocksalt and fluorite he found to be "colorless" whereas soot was opaque to rays of every color. This great similarity between infrared and visible radiation convinced him that they were the same phenomenon.

Fizeau and Foucault demonstrated the interference of two beams of infrared radiation by measuring with a very sensitive thermometer the fluctuations of temperature in the interference bands. They then studied the infrared part of the sun's spectrum and located several strong Fraunhofer lines. There soon followed a large number of researches on the transmission of many substances and also various attempts to determine the absolute wave-lengths of the infrared radiation. Since nearly all of these studies were made with the emitted radiation undispersed, they are of little value.

In 1840, J. F. W. Herschel announced in a paper read before the Royal Society that he had succeeded both in making visible the infrared rays discovered by his father and in proving that they are not continuous but consist of several groups of rays. His ingenious method was a type of photography which has formed the basis for some very successful experiments recently made by Czerny, and which will be discussed later. Herschel allowed the sun's spectrum to fall upon a piece of paper which he had previously coated with soot and dampened with alcohol. The alcohol evaporated fastest where the radiant energy was concentrated and absorbed by the soot, thus leaving dry spots (Fig. 2). In agreement with the results previously published by his father a long, dry band was obtained extending from the violet throughout the visible spectrum and out beyond the red. In fact, as Fig. 2 shows, the most intense heating occurred beyond the red end. He pointed out that the

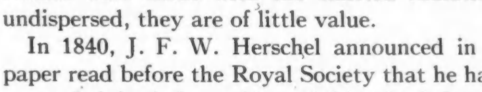

FIG. 2. J. F. W. Herschel's picture of the sun's spectrum, produced by the differential evaporation of alcohol from a soot layer.

regions in between the dry spots, regions in which very little heat was present, represented Fraunhofer lines and were caused by absorption of the radiation by the atmosphere of either the sun or the earth. Although several other investigators failed in their attempts to repeat this important experiment, Czerny's recent experiment has proven the value of Herschel's work.

Dispersion measurements

The third important chapter in this history begins with the work of Langley. In 1849 Svanberg constructed the very sensitive instrument known as the bolometer. He made no use of this instrument, however, and in 1881 Langley rediscovered it. In a series of papers Langley reported the results of careful measurements of the spectra of the sun and the moon, and of the emissions of many substances when heated to various temperatures.

The bolometer, which is in reality merely a very delicate resistance thermometer, supplied infrared investigators with a detecting device of sensitivity many times that of any instrument previously used. Measurements could be made even when the emitted radiation had been considerably dispersed. There was accordingly an immediate need for accurate measurements of the dispersion of those substances that had been found suitable for prisms and these were furnished by Langley, Rubens, Trowbridge, Paschen, and others, for quartz, fluorite, sodium chloride, and potassium chloride. Their work was of such an excellent nature that the values are still in use today. Many years were required for the completion of these measurements which were finally extended in the case of KCl to a wave-length of 22μ (22×10^{-4} cm).

Early applications

The bolometer, which had been used so successfully, was soon forgotten and a more sensitive form of the thermopile brought back into use by Rubens and others. A combination of a thermocouple and a moving coil galvanometer—the microradiometer—was later introduced by C. V. Boys; this instrument is in use today and rivals the most sensitive of our receiving devices. The radiometer, a form of the old Crookes "light mill," was also introduced by Rubens and proved itself to be of great value as an extremely sensitive heat-detecting device.

Equipped with these sensitive instruments, many workers now entered the field, and a great number of investigations were carried out, principally in two directions: the extension of the infrared to still longer wave-lengths; and the study of the absorption of infrared radiation by various solids, liquids and gases.

Undoubtedly the most successful worker in extending the infrared to longer wave-lengths was Rubens.[3] In 1897 he carried out his first experiments on selective reflection. From the dispersion measurements which had previously been made one could predict that NaCl and KCl should possess a region of selective reflection somewhere far out in the infrared. Rubens located such regions at 52 and 61μ. For these wave-lengths NaCl and KCl have a reflectivity of approximately 80 percent, whereas for other wave-lengths the percentages are very low. Rubens called these reflected beams of energy *reststrahlen*, and located the reststrahlen for some 30 crystals. He developed this method of monochromatizing the infrared into a powerful tool with which he and his co-workers were able to work as far out as 150μ. Rubens and Wood[4] made use of the difference in refractive indices of a quartz lens for visible light and infrared and were able to isolate from a Welsbach mantle radiation of wave-length 110μ. Later, Rubens and von Baeyer[5] showed that the infrared radiation emitted by a quartz mercury lamp consisted of two strong maximums at 218 and 343μ. Nichols and Tear[6] filtered these radiations through 4 layers of black paper and 8 mm of fused quartz and thus detected energy as far out as 420μ. These long waves bridged the gap that had existed between the infrared and the Hertzian waves, the shortest of which were 100μ in length and were produced in 1924 by Glagolewa-Arkadiewa.[7]

The pioneers along the other line of investigation, namely the study of the absorption of various substances, were Julius, Ångström,

[3] Rubens and Nichols, Wied. Ann. **60**, 418 (1897).
[4] Berl. Ber. 1122 (1910).
[5] Berl. Ber. 666 (1911).
[6] Astrophys. J. **61**, 17 (1925).
[7] Zeits. f. Physik **24**, 153 (1924).

Paschen and Coblentz. Julius[8] found that all organic compounds that contained a CH_2, CH_3, etc., group had similar spectra, a fact which today plays a basic role in our infrared analysis of molecular structure. Paschen's[9] extremely accurate work on the dispersion of fluorite has already been mentioned. By studying the emission of solid bodies at various temperatures, he successfully determined the function in Kirchhoff's law and obtained for it the same expression as that obtained theoretically by W. Wien. Coblentz published in 1905 the results of an extended investigation, in which he measured the transmission of a large number of compounds from 1 to 16μ. These results together with similar measurements of the emission and the reflection of many substances were published in three volumes by the Carnegie Institute[10] and form today the foundation of every beginner's knowledge of infrared spectra.

With a mere mention of the work of Eva von Bahr who showed that an infrared band consisted of many fine lines, of Pfund and Schaefer who showed independently that all compounds possessing a radical such as the SO_4, CO_3 or NO_3 groups had similar spectra, and the work of Lummer and Pringsheim whose exact measurements of the emission of black bodies paved the way for Planck's radiation formula and the quantum theory, we may consider that the historical development of the infrared has been sufficiently emphasized.[11]

Methods of Studying Infrared Spectra

Sources

Very early in the history of the infrared, the experimental laws now commonly referred to as Kirchhoff's law, Wien's displacement law, and the Stefan-Boltzmann law were discovered, and it became evident that the best source for use in the infrared was a "black body." Various attempts were made by Wien, Lummer, Pringsheim, Kurlbaum and others to construct such sources. These were usually in the form of electrically heated ovens, one end of which had a window out of which the radiation emerged. They were practically perfect black bodies. In practice today, however, one generally uses a small strip of hot platinum or a rod of carborundum known as a "glo-bar." These sources, while not really "black," may be operated at about 2000°K and have been found satisfactory wherever calculations as to the exact emission of the source are unnecessary; for spectroscopy they have the advantages that they are small, may be effectively shielded and may be given a shape similar and comparable to that of the slit of the spectrometer. Another source is the Nernst filament, which is a thin filament made of a paste of cerium, thorium, and zirconium oxides and operated at about 2400°K. The emission of this source corresponds closely to that of a black body, but because of its delicacy and the ease with which it burns out, is gradually going out of use. All of the foregoing sources, when operated at the temperatures mentioned, are rich in near-infrared energy. Their use in the far infrared, which extends from about 20 to 500μ, is not to be recommended.

As may be seen from Fig. 3 the far infrared is primarily the region of gratings. Gratings, as is

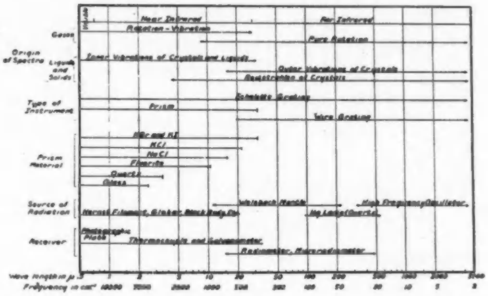

FIG. 3. The infrared spectrum. Many of the regions must be regarded as only roughly defined by the markings in this diagram.

TABLE I. *Relative intensities of a black body at 2000°K* (*Eucken-Wolf*[1]).

Wave-length, μ	I, relative
1.44	1
2	8×10^{-1}
5	9×10^{-2}
10	9×10^{-3}
50	2×10^{-5}
100	1×10^{-6}
200	8×10^{-8}

[8] Konikl. Akad. Amst. I, No. 1 (1892).

[9] Wied. Ann. **56**, 762 (1895).

[10] *Investigations of Infrared Spectra* (Washington, 1905–08).

[11] For a most interesting and complete account of the history of spectroscopy the reader is referred to Kayser's *Handbuch der Spectroscopie* (1900), Chap. 1.

well known, superpose spectral orders. Table I shows how careful one must be not to have any of the higher ordered spectra present while working in the far infrared. Remembering that the intensities of the various orders n of a grating spectrum fall off as $1/n^2$, we see[12] that the 10*th* order of 10μ will still be 9×10^{-5} as compared with 1×10^{-6} for the first order of 100μ. The energy of the near infrared must therefore be eliminated completely if one is to work in the long wave region. This is accomplished by a combination of several methods.

Fortunately, there is available as a source the Welsbach mantle, whose emissivity, while very nearly zero for the region 1–6μ, approaches the value 1 for wave-lengths longer than 20μ. Here is a source that gives almost the maximum energy possible for the long wave-lengths, but a minimum of energy in the near infrared. The temperature of such a mantle is estimated to be 1800°K. Obviously, the emission of the gas flame, which arises chiefly from the H_2O and CO_2 bands near 1.5, 2.7, 2.9 and 4.4μ, is superposed upon that of the mantle, and so some short wave-length energy actually is present. This energy may be partly eliminated by operating the mantle in a hydrogen flame or even an electric arc, but other methods must generally be employed to remove it completely.

Receiving devices

The most common apparatus for detecting infrared energy is a sensitive thermopile in series with a galvanometer. The thermopile, which may be bought or made locally, usually has a receiving area that is shaped like the spectrometer slit. This area, which is made up of the "hot" junctions in a row, must be properly blackened. The most sensitive junction which is in great use consists of two alloys known as Hutchins' alloys; these are (95Bi+5Sn) and (97Bi+3Sb). This combination has a rating of 120 μvolts per degree difference in temperature of the two junctions. Many types of couples have been used successfully, and the reader should consult the literature cited in the treatises on the infrared before attempting to construct

[12] A further reduction of the intensity of the overlapping orders arises from the difference in dispersion in the first and nth orders. The relative spectral slit widths in these two cases must be considered.

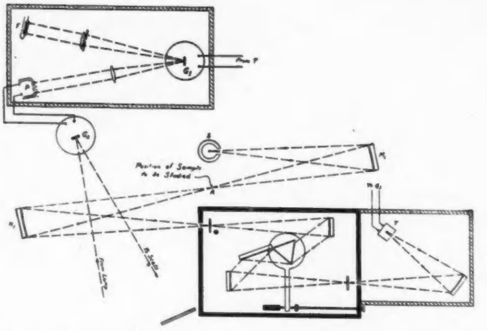

FIG. 4. A typical rocksalt prism spectrometer, using the Wadsworth mounting and a photoelectric amplifier.[14]

one. Besides the choice of materials, one has to settle the problems of the dimensions, losses of heat by conduction along the wire and losses through the air (whether to evacuate or not), the resistance, etc. Such a device obviously must be shielded from stray heat and from pressure changes. It is surprising, but very easy to demonstrate, that if the thermopile is not enclosed in a vacuum-tight container, the galvanometer will register all fluctuations of pressure in the room. In the instrument last used by the authors, for example, with the container open to the air a deflection of 10 cm was obtained upon opening the door to the room, due to the change of temperature caused by the adiabatic pressure change. The deflection of the galvanometer may be amplified by any one of several methods up to the point where the unsteadiness of the building and eventually the Brownian motion of the galvanometer itself become noticeable.[13]

The instrument devised by Boys, the microradiometer, is also frequently used. It is a combination of a thermocouple and galvanometer, so constructed that the suspended coil, which consists of a single turn of wire, is cut on the lower side and joined together by a suitable thermocouple. Because of its low resistance this instrument may be made extremely sensitive. It is always used evacuated in order to reduce the heat losses through the air and the resistance to the turning of the coil.

Still another receiving device is the radiometer. Here again one must proceed carefully and be fully informed if a really sensitive instrument is to be constructed. The dimensions of the entire system are small and the quartz suspension is extremely delicate. Since the radiometer

[13] Ising, Phil. Mag. **1**, 827 (1926); Ann. d. Physik **8**, 911 (1931).

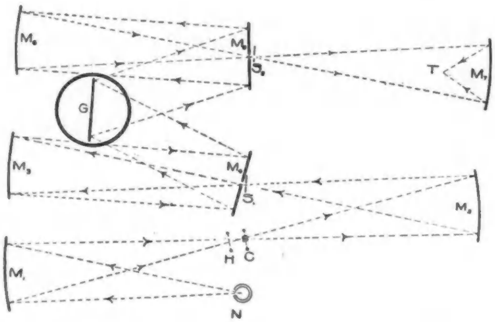

FIG. 5. An echelette grating spectrometer.[15]

depends for its action both on the presence of gas molecules and a low viscosity of the surrounding medium, the sensitivity is a function of the pressure. It usually is maximum at pressures of 10^{-1} to 10^{-2} mm of mercury. The stiffness of the quartz fiber, the moment of inertia of the system, the pressure, etc., all play major roles where the period of the instrument is concerned. Radiometers may of course be used together with some amplifying system but are usually so sensitive as to allow an amplification of only ten to twenty times before the unsteadinesses previously referred to become important.

Spectrometers and methods

Many types of spectrometers are available, the selection of the one to be used being determined by the type of spectra to be measured and the degree of accuracy required. Although practically every investigator designs and constructs his instrument to suit particular needs, there are several standard spectrometers on the market. Only the general types will be outlined here.

Prism spectrometers. Fig. 4 shows a typical prism instrument.[14] The radiation which emerges from the second slit may be seen to have traversed the prism at minimum deviation. This is accomplished by the Wadsworth mirror, and greatly simplifies the calculation of the wave-length of the emergent radiation. Such an instrument may be calibrated by mapping the positions of known absorption bands such as those of H_2O, CO_2, etc., or, if a divided circle is present, the wave-lengths may be calculated. The former method is most frequently used. As is indicated in Fig. 3 and Table II, several materials are available for use as prisms. Since the resolving power of a prism is a function of

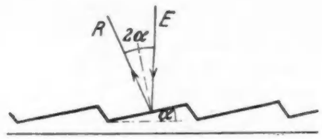

FIG. 6. Groove form of an echelette grating. E and R are the incident and the reflected beams; 2α is the blaze angle.

the thickness of the base of the prism, and since these substances may not be had in very large pieces, the usefulness of prism spectrometers is quite limited. They are valuable, however, for a preliminary survey of the near infrared and for many problems where the fine structure of the bands being studied is unimportant. To protect the prism, to eliminate convection currents of air, and to remove the water vapor, the instrument should be enclosed in a tight, thermally insulated box and dried with P_2O_5.

Echelette grating spectrometers. If one is interested primarily in obtaining exact measurements in some particular region of the near infrared, a spectrometer of the design shown in Fig. 5 is used.[15] It employs a reflection grating, usually one of the echelette type, which has the peculiar property of concentrating practically all of the incident energy into a restricted spectral region, called the *blaze*, on one side of the central image. This is accomplished in the process of ruling the grating by holding the cutting diamond at such an angle as to give the grooves a form very nearly like that indicated in Fig. 6. The first of these gratings was constructed at Johns Hopkins University by R. W. Wood, from whom they may be purchased today. By adjusting the angle of the diamond the blaze may be placed at any desired wave-length throughout the near infrared. These gratings are ruled upon highly

TABLE II. *Available prism materials and their practical limits of usefulness.*

Material	Limit, in μ
Glass	2.5
Quartz	3.5
Fluorite	9
NaCl	16
KCl	22
KBr	28
KI	31

[14] Barnes, Brattain, and Seitz, Phys. Rev. **48**, 582 (1935)

[15] Barnes, Phys. Rev. **36**, 296 (1930).

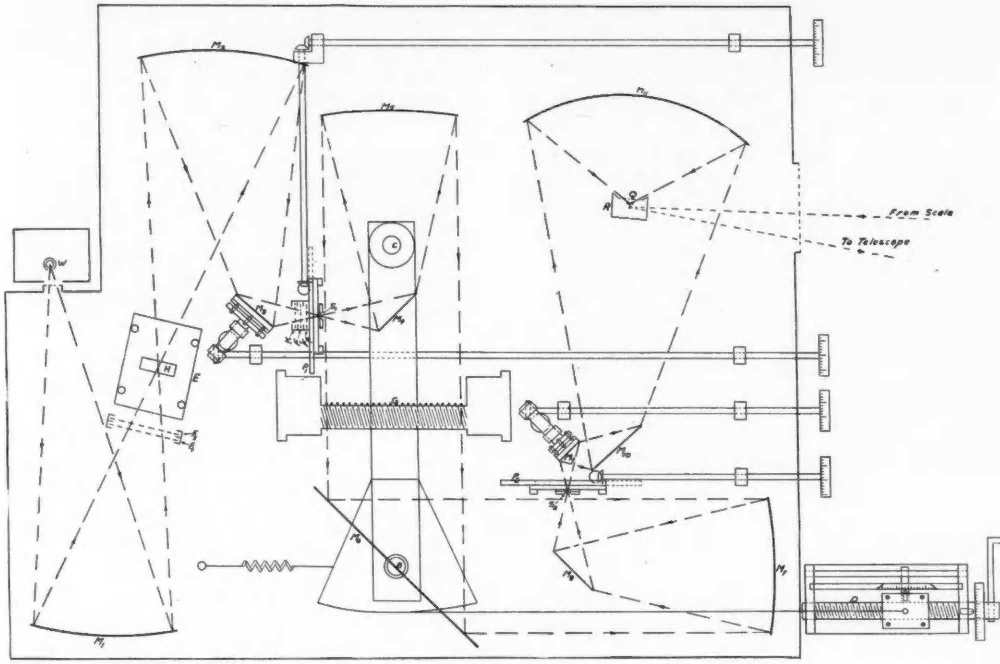

FIG. 7. A wire grating spectrometer for the far infrared.[17]

polished copper blanks, and may have as many as 7200 lines/in. Since the resolution of a grating is equal to the total number of lines used, one has with a 5-in. grating an instrument capable of yielding results of the highest precision. It is only with such spectrometers that there is hope of measuring accurately the fine structure of the rotation-vibration bands, or the shifts caused by isotopes such as Cl^{37}. Since the determination of the character of the fine structure of any given band in the near infrared is of the utmost importance for making the final decision as to its type and origin, a good echelette grating spectrometer is indispensable for work in this field.

Another form of echelette grating[16] consists of a pile of glass plates of suitable thickness, so arranged as to allow the radiation to be incident upon the edges which present a cross section similar to Fig. 6. Many such gratings have been devised but so far good results have been obtained only with ruled gratings.

Wire grating spectrometers. When one attempts to work in the far infrared, the difficulties mount rapidly. The Johns Hopkins machines have not yet made echelettes for this region and the University of Michigan machines have ruled successfully only a few such gratings for regions out to 100μ. Hence it is necessary for the present to rely mainly upon wire gratings similar to the original ones prepared by Fraunhofer. One of the authors[17] has constructed such gratings having as many as 64 wires/in. and has used them successfully throughout the region 30–180μ. Fig. 7 shows a spectrometer suitable for use with these gratings. With an 8-in. grating the theoretical resolving power is 500, which at 100μ represents a wave number separation of $0.2\ cm^{-1}$. This is never attained, of course, owing to the widths of the slits that are necessary in order to obtain a measurable amount of energy. Spectral lines have, however, been completely resolved in this region whose separation was $1.33\ cm^{-1}$. Other lines at 150μ have been shown to be double

[16] Badger, Proc. Nat. Acad. Sci. **13**, 408 (1927).

[17] Barnes, Rev. Sci. Inst. **5**, 237 (1934).

when the separation was 0.5 cm^{-1}. The authors are at present putting a spectrometer into service that promises to surpass even this.

Reflection gratings. Many methods have been suggested for making reflection gratings for this region, but so far no results have been obtained with them. Gratings recently described by Pfund and Sanderson[18] show promise, however. They are prepared from the half-tone plates used in color printing and known as Levy Screens.[19] According to Pfund the screens need only be silvered or, better still, aluminum plated before being used. The ruled places scatter the radiation and the unruled portions act specularly as bright silver bars, thus producing exactly the same type of spectra as the wire grating. The accuracy with which the lines are spaced and the increased number of lines per inch, bids fair to make these gratings replace the wire gratings for use in the far infrared.

Method of reststrahlen. There is a method of making survey and other measurements in this part of the spectrum where the question is merely whether or not a certain body absorbs or transmits the far infrared. It is the method originally used by Rubens in his pioneer work in this region, namely, the method of reststrahlen. A convenient spectrometer[20] for this purpose is shown in Fig. 8; one of its advantages is that only very small crystal plates are necessary. Schaeffer and Matossi[1] give a list of some 33 reststrahlen between 20 and 150μ. Although the method often can be used quickly and to advantage, its obvious disadvantages are that so few wave-lengths can be examined and that the reflected energy is not monochromatic, but may include an interval of 15 to 20μ.

Christiansen filters. Experiments are in progress on the use of Christiansen filters in the infrared.[21] If a thin film of a finely powdered crystal, say quartz, is deposited upon some suitable holder, such as a film of nitrocellulose or a plate of NaCl, it will be found to have remarkable transmission properties. If the particles are very much larger than λ_O, the true absorption wave-length of the crystal, the film will be quite opaque, because the small particles refract the radiation in all directions and thus allow very little of it to reach the slit of the spectrometer. On the short wave-length side of λ_O, however, the refractive index of the particles decreases rapidly and at some one wave-length becomes equal to 1. At this wave-length, λ_{Chr}, since the indices of the particles and surrounding medium are equal, no refraction occurs and the film shows a sharp, high transmission maximum. For quartz this maximum is decidedly sharper than the reflection band, and has a value of about 75–80 percent. If the method is developed properly one would only need to prepare a series of such filters, and then use a source, filter, mirror and receiving device. The method would be much simpler than that of reststrahlen.

Photographic infrared spectrographs. At the present time one of the most valuable sources of information concerning the fine structure of infrared bands, is a study of the overtones and combinations of these bands which occur in the photographic region, that is, from the visible region out to 1.3μ. The recent progress in the sensitization of photographic plates has made it possible to use the large optical gratings out as far as 1.3μ, and so to obtain a degree of resolution heretofore unknown in the infrared. As a result a great many of the fine-structure problems which were previously beyond solution are now easily mastered. The plates used are easily fogged at room temperature and must be shipped and stored at "dry ice" temperatures. It appears that we may not hope to be able to photograph much further out than 2 or 3μ since a limit is

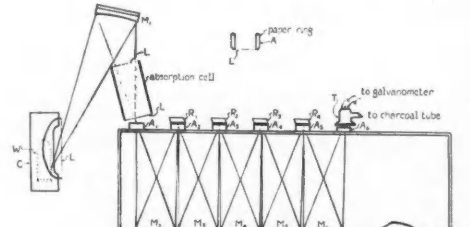

FIG. 8. A reststrahlen spectrometer. (Strong).

[18] Phys. Rev. **47**, 792 (1935).
[19] These screens may be obtained from Max Levy, Philadelphia, Pa., up to 10×10 in. and containing as many as 350 lines/in.
[20] Strong, Phys. Rev. **37**, 1565 (1931).
[21] Barnes, Brattain and Firestone, Phys. Rev. **47**, 792 (1935).

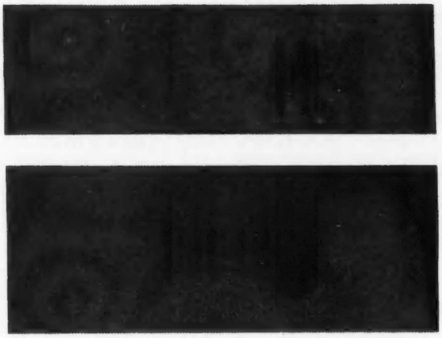

FIG. 9. The absorption bands of napthalene. The upper photograph shows the bands in the region 3μ; the lower, with longer exposure, shows bands out to about 6μ.

set by the intensity of black body radiation at room temperature.

Czerny's photographic method. There does exist, however, one method of photographing farther out in the infrared. As mentioned previously, Czerny[22] has recently improved upon the younger Herschel's original method and obtained photographs out to 7μ. The principle is quite simple. The desired radiation is allowed to fall upon a specially prepared film having soot on one side and naphthalene on the other. The naphthalene sublimes away from those spots where the most intense radiation falls, and the film may then be photographed by an auxiliary camera. Fig. 9, taken from Czerny's original paper, shows the absorption bands due to the naphthalene out to 6μ. Fig. 10, taken from a paper by one of Czerny's students,[23] shows the 3.5μ rotation-vibration band of HCl. At this time the method had been modified, a film of oil having replaced the naphthalene. This greatly increased the sensitivity of the process, for only enough oil had to evaporate to change the color of the interference bands of the film. Before the exposure these of course were so broad as to make the entire film appear in one color. This method is a most promising one and deserves further development, for with long enough exposures one should be able to go quite far into the infrared. At present the exposure time is limited to about 15 min., for after that time the oil begins to flow back into the valleys where the radiation has fallen.

[22] Zeits. f. Physik **53**, 1 (1929).
[23] Willenberg, Zeits. f. Physik **74**, 663 (1932).

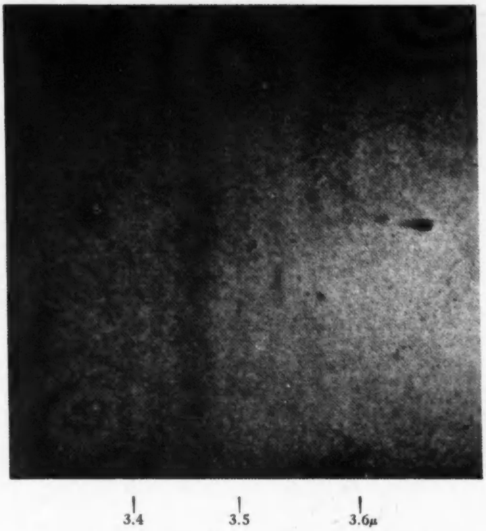

FIG. 10. Photograph of the 3.46-μ HCl band.[23]

Experimental procedure. In using any of the foregoing methods, other than the photographic ones, the actual procedure followed is practically the same. In an overwhelming majority of the problems attacked, investigators must be content with an exact determination of the wave-lengths of the various absorption bands and a relative determination of their intensities. Until we have more quantitative information concerning the emission of our sources, the losses of energy in the various parts of the apparatus, and the degree of "blackness" of our receiving devices, absolute intensities will be inaccessible. In studying absorption a percentage transmission curve is actually mapped out by means of some device that enables the sample to be brought into and out of the path of the radiation at will. At every wave-length, measurements are taken with the cell "out," then "in," and the ratio taken. Reflection powers are determined by comparing the deflections obtained at each wave-length from the surface of a freshly silvered mirror with those obtained from a surface of the unknown. In this way solids or liquids may readily be measured. Absorption measurements are usually carried out at room temperature although arrangements are sometimes made for controlling the temperature of the sample.

High School Physics as a Preparation for College Physics*

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BECAUSE of the differences in opinion among college teachers of physics as to the value of high school physics as a prerequisite to college physics, one may expect that colleges will differ in practice as to the treatment of offerings in high school physics. For example, some physics departments have separate sections in general physics for the students who have had high school physics. The student often sees little connection between the technical college course in physics with its absolute units and the essentially non-technical high school course with its practical system of units.

Tests on the correlation of training in mathematics with grades in college physics have been more common recently than corresponding tests on high school and college physics. Thus, poor grades in physics have been traced to previous preparation in mathematics by Lemon.[22] Bless[4] concluded from a series of cooperative tests with different institutions that the average grade made in physics was, essentially, directly proportional to the grade representing the mathematical preparation of the student.

A study of the effect of high school physics was undertaken by Colmey[8] in 1919 at the University of Illinois. By means of a questionnaire each student was asked if he had had high school physics and, if so, whether it had helped him. The questionnaire was sent to each student taking physics for the school years 1914–15 to 1918–19, including in all 771 students. The Registrar's files were examined for records of their grades in physics. The general conclusion was that high school physics was of no benefit to those whose records were examined at that time and that there should be no separation of students on the basis of high school physics.

Caswell[7] makes the statement: "I have yet to find that high school physics is an indispensable prerequisite. On the other hand, I have repeatedly found that a good student who has never had high school physics will do better work than one who has had such a course." Garrison[15] states that "Crudrup studied the records of 906 students in first year college physics. About half of this group had previously studied high school physics but, for a given mental ability, they showed no superiority over the remainder of the group. Harvey has found that students who have not had high school physics obtain more accurate data and get better results in the college laboratory."

Procedure and Data

The author has made a study of the possible effect of high school physics on the final grade in college physics by means of certain sampling tests in physics and in mathematics. These tests have been conducted at two universities over a period of four years. A sampling examination, consisting of simple mathematical calculations and of physics questions, was given to each student at the first meeting of the class. The first series of tests was very similar to the tests given by Lemon.[22] The examinations have been modified from time to time. In 1927–28 there were 10 possible points in physics and 14 in mathematics, and in 1928–29, 15 possible points in physics and 14 in mathematics. With the exception of 1 question in the physics test which counted for 2 points, each point represented a question. At the end of the first semester, the final college physics grades were compared with the sampling examination.

It is assumed in what follows that the sampling tests represent reasonably well the students' preparation in high school physics and in mathematics. No attempt will be made to justify the use of the word "preparation" instead of "intelligence" or "aptitude" in the foregoing statement. What we are dealing with here is a distribution of students commonly encountered in a university, assumed to be reasonably typical. This is the situation about which we commonly hear the expression that high school physics has no value as a prerequisite to college physics while for the same students, mathematics as a prerequisite apparently does have some value.

The tests were conducted the first semesters of the years 1927–29 at New York University and the first semesters of 1933–35 at the Uni-

* Paper No. 441, Journal Series, University of Arkansas.

TABLE I.

Years	Percent. distribution of grades in the sampling phys. test	Av. final college phys. grade for those finishing course	No. of students	Percent. distribution of grades in the sampling math. test	Av. final college phys. grade for those finishing course	No. of students
1927–29	Low 25%	65.6	126	Low 25% Med. 50% High 25%	61.2 65.5 70.5	31 64 31
	Med. 50%	67.5	344	Low 25% Med. 50% High 25%	65.2 66.8 70.4	87 157 100
	High 25%	72.7	159	Low 25% Med. 50% High 25%	65.7 72.7 79.9	40 79 40
1933–35	Low 25%	3.47	31	Low 25% Med. 50% High 25%	2.30 3.54 4.50	8 15 8
	Med. 50%	4.82	54	Low 25% Med. 50% High 25%	3.72 4.85 5.93	14 27 13
	High 25%	6.23	30	Low 25% Med. 50% High 25%	4.14 6.26 8.00	7 15 8

versity of Arkansas. The results have been tabulated in different ways to bring out points that it is desirable to emphasize. Thus, Table I is arranged so that all students receiving grades in the sampling physics tests may be separated as nearly as possible into three groups: (1) the 25 percent receiving the lowest grades, (2) the 50 percent receiving medium grades, (3) the 25 percent receiving the highest grades. It will be noticed that the average college physics grade is improved whenever the sampling examination indicates a better preparation in high school physics. An attempt is made in Table I to separate also the effects of preparation in mathematics from preparation in high school physics. Thus, each of the three physics groups is subdivided again so that all students in each of these groups may be separated in accordance with the sampling mathematics test into the 25, 50 and 25 percent with the lowest, medium and highest grades, respectively. For each of the three grades of accomplishment in high school physics, the effect of mathematical preparation is shown in the right half of the table.

Since the method of grading is not the same at the two universities, the magnitudes of the numerical grades for the years 1927–29 and 1933–35 are not comparable. The Missouri system is used at Arkansas. Therefore, it was found convenient to use the following notation for the 1933–35 tests: $A=9$, $B=7$, $C=5$, $D=3$, $F=1$. A numerical system with intervals of 0 to 100 was used at New York University.

Table II deals with essentially the same group as Table I, but here the positions of the sampling mathematics test and the sampling physics test are interchanged. There are two places in Table II where the average final college grade is not as high as might be expected in comparison with the rest of the data. In view of the relatively small numbers tested, the point is not considered significant. Moreover, each instructor gives his own examination at Arkansas and grades his own papers. At New York University, all students took the same final examination and each instructor graded one question only on all papers. It was hoped that if previous preparation in mathematics and high school physics embraced half or more of the essential prerequisites for college physics, Tables I and II would show the essential contribution of each subject. The results indicate that good work in high school physics, as well as in mathematics, will improve the grade in college physics.

Correlation coefficients were found by the usual methods between the tests for pre-physics

TABLE II.

Years	Percent. distribution of grades in the sampling math. test	Av. final college phys. grade for those finishing course	No. of students	Percent. distribution of grades in the sampling phys. test	Av. final college phys. grade for those finishing course	No. of students
1927–29	Low 25%	63.3	156	Low 25%	60.7	36
				Med. 50%	63.7	88
				High 25%	63.3	32
	Med. 50%	67.6	330	Low 25%	65.1	82
				Med. 50%	67.1	165
				High 25%	70.8	83
	High 25%	73.6	151	Low 25%	69.5	37
				Med. 50%	73.5	77
				High 25%	77.8	37
1933–35	Low 25%	3.44	27	Low 25%	2.43	7
				Med. 50%	4.17	12
				High 25%	3.25	8
	Med. 50%	4.86	57	Low 25%	3.80	15
				Med. 50%	4.75	28
				High 25%	6.21	14
	High 25%	6.22	28	Low 25%	4.14	7
				Med. 50%	6.29	14
				High 25%	8.14	7

and post-physics, for pre-mathematics and post-physics, and for pre-mathematics and pre-physics. The results appear in Table III. The magnitude of the correlation coefficients indicate that there are other important factors effecting the final grades in college physics in addition to high school mathematics and high school physics. It is probable that there is no single factor in education, such as a course in mathematics, by which success in physics may be predicted. The correlation coefficients for the individual sections ranging in numbers from 7 up to 63 varied from a negligible or negative quantity up to 0.92. Of the 23 sections tested, 1 pre-physics and post-physics, 2 pre-mathematics and post-physics, and 3 pre-mathematics and pre-physics correlation coefficients were negative. There were no negative correlation coefficients in any of the Arkansas sections. The tests used at New York University, 1928–29, and at Arkansas, 1933–35, were the same.

Discussion and Conclusions

There are certain important differences in the preparation of students taking elementary physics at New York University and at Arkansas. Considerable more mathematical preparation is possible for the New York University students since they take physics in the sophomore year; about two-thirds of these students had more than one semester of college mathematics. On the other hand, the engineering students at Arkansas take physics in the freshman year while the pre-medical students, who generally are not interested in mathematics, have the same course in the sophomore year. The advantage of the additional training in mathematics is clearly indicated by the average grade received at the two institutions in the same sampling mathematics tests. For those having had high school physics the average of the grades in the same sampling physics examination at each of the institutions showed no substantial difference. The data discussed in this paragraph are based on approximately 310 students at New York University and 110 students at Arkansas.

TABLE III. *Correlation coefficients.*

Institution	1st sem.	No. of students	Correlation coefficients: Pre-phys., post-phys.	Pre-math., post-phys.	Pre-math., pre-phys.
N. Y. U.	27–28	337	0.28	0.22	0.083
N. Y. U.	28–29	310	0.35	0.34	0.29
U. of A.	33–35	102	0.53	0.46	0.38

Colmey[8] used a questionnaire to find out what the students thought of their high school course after having taken a college course in physics. He asked the question, "Do you think high school physics work has helped you in this work?" Typical answers he received are quoted in part as follows:

To a great extent, it has. It was, however, taught so differently in high school that it had to be learned anew.

Decidedly not! It seems to be doubly hard to unlearn some things and it also seems that many things were wrongly developed in high school.

Yes. The fundamental ideas are much easier to grasp.

Yes, even though much of the work taken up in the university is new and all of it is more in detail. Knowing the proper names and the fundamental laws from high school physics, one has a feeling of familiarity with the subject.

It has helped in the way of giving me a general idea of the different parts of the subject. It has given me the idea that I know enough about it to allow myself to loaf.

It gives me a general but rather hazy idea. I think that I would study more and get more out of it, if I hadn't had it in high school, or if it were taught a little more thoroughly there.

No. The high school course was very weak.

As a curiosity, yes. Theoretical side of subject not sufficiently developed in high school to be of any value.

One might ask whether the root of the difficulty in the transfer of the concepts obtained in high school physics to those of the college course is not to be found in the emphasis placed on the many systems of units used in the usual college course. Many mathematical situations are presented to the student to emphasize the use made of different systems of units. It is not improbable that considerable of this kind of mathematics is introduced into physics courses in college to the detriment of stressing physical concepts, especially by the experimental demonstration method. Many students who have had high school physics say that they have had but little practice in problem work, perhaps no problem work at all involving second degree equations. It is probable, then, that problem work associated with absolute units in particular will have but little if any direct correlation with the student's high school physics experience.

It is impossible to expect, or even desire, that all students who take general physics will be technically minded. The average non-technical student has great difficulty in understanding the point of view of college physics and would benefit but little in examinations even by repeating the college course, judging by repetitions of low grade students in physics. It is perhaps better to teach in our colleges technical courses in physics for engineers, physical science majors and minors, and premedical students and to give "everyday" physics to other students. A large number of technical words used in physics are not found in ordinary language and many of them are used but once. A less technical physics should appeal to the non-technical student. This "everyday" physics would stress concepts and principles by the lecture demonstration method without emphasis on problems, especially problems of the technical type. In such a course, the practical system of units should be used. The course may and possibly should be given a credit not in excess of six semester hours.

The data presented here are significant especially to those who hold that mathematics is definitely a more important contributor to higher final college physics grades than high school physics. The results, in this respect, are noncommittal. Therefore, for college physics students with prerequisites similar to those represented in this paper, a separation into divisions based on credit received from high school physics appears to be justified to about the same extent as a separation on the basis of mathematical preparation. A qualifying examination or a series of qualifying examinations seems to be a more logical method of separation.

The common statement that high school physics has no value for those taking college physics is therefore not confirmed. Compared with the effect of mathematical preparation, as received by the students tested, the effect of high school physics on the final college physics grade for the first semester is shown to be comparable or nearly comparable for success.

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The Gibbs and Mollier Thermodynamic Surfaces

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IN a recent issue, F. L. Verwiebe[1] described a model of the well-known thermodynamic surface obtained by plotting the equilibrium values of pressure P, volume V and temperature T of a pure substance along rectangular axes. A model of such a surface for water has been used profitably at this institution for some time in conjunction with an undergraduate course in heat and thermodynamics. It is the purpose of this paper to describe two other surfaces, plotted along rectangular axes, which are not so well known but which also have been found to be of value in undergraduate teaching. These are: the *Gibbs surface*, in which energy U, volume V and entropy S are plotted; and the *Mollier surface*,[2] generated by plotting values of enthalpy H, entropy S and pressure P.

The models are not meant to be quantitatively correct but merely to represent in a qualitative manner the properties of water at moderate pressures and temperatures. Views of each surface are shown in Figs. 1 and 2. The surfaces were first modeled in clay. Moulds were then constructed and from the moulds plaster castings were made. When thoroughly dry the plaster surfaces were prepared for painting by smoothing them with steel tools and sandpaper. The regions representing the solid, liquid and vapor phases were painted red, blue and yellow, respectively, while those representing equilibrium between two phases were painted with the color for the one phase on which were superimposed lines of the color for the other phase. Thus, the region representing equilibrium between solid and vapor is red with yellow lines. In the case of the Gibbs surface, the "triple point" triangle was painted white. On both surfaces, the region above the critical isotherm, representing the gaseous phase,

[1] F. L. Verwiebe, Am. Phys. Teacher **3**, 179 (1935).

[2] The authors do not know who was the first to describe this surface, and have therefore named it after Mollier since the Mollier diagram, of importance in engineering, is a projection of this surface on the H-S plane.

(a) (b)

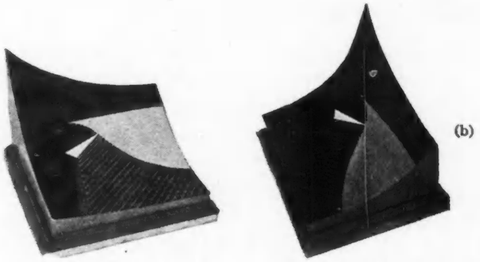

FIG. 1. Photographs showing two views of the Gibbs surface.

(a) (b)

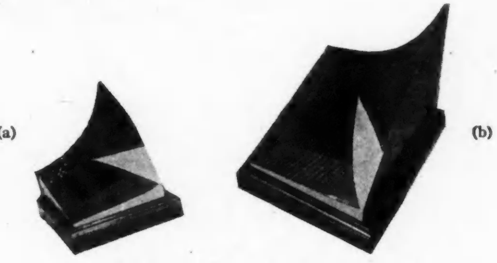

FIG. 2. Photographs showing two views of the Mollier surface.

was painted green. The photographs do not do justice to the striking appearance of the surfaces when they are colored in this way.

The Gibbs surface. The U-V-S surface[3] goes back to Gibbs' famous paper in the Transactions of the Connecticut Academy in 1873, "A Method of Geometrical Representation of the Thermodynamic Properties of Substances by Means of Surfaces." In the biographical note in the first volume of Gibbs' *Collected Works*,[3] Bumstead remarks that, "the exceptional importance and beauty of this work by a hitherto unknown writer was immediately recognized by Maxwell, who, in the last years of his life, spent considerable time in carefully constructing, with his own hands, a model of this surface, a cast of which, very shortly before his death, he sent to Professor Gibbs." The authors regret to state that they have never seen this model.

It is a well-known consequence of the two laws of thermodynamics that the change of internal energy of a constant mass of a pure substance in passing from an initial equilibrium state to an infinitesimally neighboring equilibrium state is given by $dU=TdS-PdV$. If U is expressed as a function of S and V, then

$$\left(\frac{\partial U}{\partial S}\right)_V=T \quad \text{and} \quad -\left(\frac{\partial U}{\partial V}\right)_S=P,$$

from which it follows that the temperature and pressure at any point on the U-V-S surface are determined by the two slopes of the plane tangent to the surface at that point. Thus, if U is expressed as a function of S and V, all other thermodynamic quantities may be calculated. Any function such as $U=U(S,V)$ which by differentiation permits the determination of other thermodynamic coordinates is called a characteristic function.

If U is expressed as a function of any other two coordinates, the other quantities cannot be calculated. For example, suppose we are given U as a function of V and T. Then the thermodynamic equation

$$\left(\frac{\partial U}{\partial V}\right)_T=T\left(\frac{\partial P}{\partial T}\right)_V-P$$

can be written in the form

$$\left[\frac{\partial\left(\frac{P}{T}\right)}{\partial T}\right]_V=\frac{1}{T^2}\left(\frac{\partial U}{\partial V}\right)_T$$

and then integrated at constant V. Thus,

$$\frac{P}{T}=\int\left(\frac{\partial U}{\partial V}\right)_T\frac{dT}{T^2}+F(V).$$

Since $F(V)$ cannot be determined, it follows that P and therefore the other quantities cannot be calculated even though U is known as a function of V and T.

Since Fig. 1 may give the impression of representing a surface with much relief when in fact there is none, it should be pointed out that the Gibbs surface is quite featureless and without corners, in contrast to the P, V, T surface. It is clear from Fig. 3 that the Gibbs surface consists of eight regions as follows: four regions representing the four separate phases solid, liquid, vapor, and gas; three regions each representing equilibrium between two different phases; and one region representing equilibrium among three phases. Since a constant mass of solid in equilibrium at a given temperature and pressure can exist at only one definite volume, it follows that a tangent plane touches the solid region at only one point. The same is true for the liquid, vapor, and gas regions. These four regions are therefore skew surfaces. In the region representing equilibrium between solid and vapor, a definite temperature and pressure do not determine a unique volume, but are the same for all pro-

[3] *Collected Works of J. Willard Gibbs* (Longmans, Green, 1928), Vol. 1, p. 33. In Gibbs' notation energy, volume and entropy are designated by ϵ, v, η, respectively.

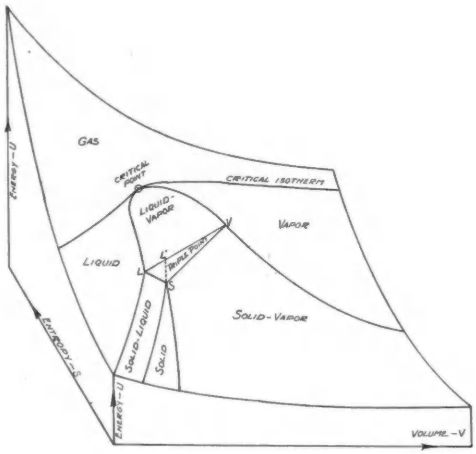

FIG. 3. Diagram of the Gibbs surface.

portions of solid and vapor. A tangent plane, therefore, touches the solid-vapor region along a line. The same is true of the solid-liquid and liquid-vapor regions. It follows that these regions are ruled surfaces. Moreover, they can be shown to be developable.[4]

Since all proportions of solid, liquid and vapor at the "triple point" are in equilibrium at the same temperature and pressure, the tangent plane characterizing this temperature and pressure touches the surface at all of these points. The "triple point" is therefore, a plane triangle. It is to be noted that the small side SL of the "triple point" triangle is inclined in such a manner as to show that liquid water expands upon freezing. In the case of other substances such as CO_2 this line would be inclined in the direction of the dotted line SL′. The critical isotherm is shown passing through the critical point. Its projection on the U-V plane approaches a horizontal line as V becomes large, because, for large values of V, a gas behaves approximately like an ideal gas for which $(\partial U/\partial V)_T=0$.

The Mollier surface. If we define the enthalpy[5] by the equation $H=U+PV$, then the change of enthalpy of a constant mass of a pure substance between two infinitesimally neighboring equilibrium states is given by[6] $dH=TdS+VdP$, and, if H is expressed as a function of S and P,

$$\left(\frac{\partial H}{\partial S}\right)_P=T \quad\text{and}\quad \left(\frac{\partial H}{\partial P}\right)_S=V.$$

It follows that the temperature and volume corresponding to any point on a H-S-P surface are represented by the slopes which determine a plane tangent to the surface at the given point. It is evident that H expressed as a function of S and P is a characteristic function.

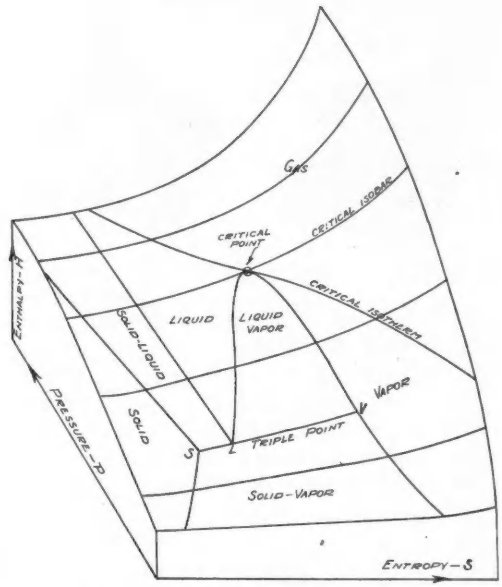

FIG. 4. Diagram of the Mollier surface.

The same regions mentioned in regard to the Gibbs surface can be seen in the sketch of the Mollier surface shown in Fig. 4, along with a few typical isobars. This surface is also without corners. On the Mollier surface the "triple point" is a line normal to the P-axis with slope $(\partial H/\partial S)_P=T^*$, where T^* is the "triple point" temperature. The projection of the isobaric lines on the H-S plane gives the Mollier diagram, a portion of which is of great use in engineering in representing the properties of steam and of various refrigerants.

[4] M. Planck, *Treatise on Thermodynamics* (Longmans, Green, 1927), p. 170.

[5] The terms "heat content" and "total heat" are employed to designate the same function but are gradually being discarded.

[6] During an isobaric process the change in enthalpy is equal to the heat lost or gained by the working substance. Since $dP=0$, $dH=đQ$, where $đQ$ represents an infinitesimal quantity of heat and $H_2-H_1=Q$. This is important in steam engineering and refrigeration where many of the processes take place at constant pressure.

Rational-Sided Right Triangles

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Both teacher and student dislike numerical examples involving irrational quantities. They also tire of the 3–4–5 right triangle. The fact that there is an infinite array of rational-sided right triangles does not seem to be generally known, if the failure of the physics textbooks to use them is any criterion. A simple method of finding these triangles follows.

Let a, b, c be the legs and hypothenuse, respectively. Then

$$a^2+b^2=c^2, \quad \text{or} \quad a^2=(c-b)(c+b).$$

Now, let $(c-b)$ be a fixed number n, and let a be given a series of values. We have then merely the problem of finding two numbers, b and c, such that

$$\begin{aligned} c-b&=n,\\ c+b&=a^2/n, \end{aligned}$$

subject to the condition that a, b, c, n be whole numbers. Table I should be useful to anyone who wishes to construct problems that involve right triangles.

To avoid producing triangles that are merely similar to each other, it is necessary to impose upon a and n the restrictions stated in Table II. The complete demonstration of this is quite lengthy, but we can indicate the general method by considering three examples:

Case 1, n = odd power of 2. For example, let $n=8$, $a=4p$, where p is an odd number. Then $a^2/n=2p^2=c+b=2b+8$, or $p^2=b+4$ = odd number. Hence, b and c are both odd and can have no common factor. The triangles so obtained are therefore new ones (that is, they are not similar to any triangle having $n<8$).

But, if p be even, then we obtain by the same reasoning that both b and c are even. But $a=4p$ is given even. Therefore, a, b, c must be divisible by at least 2, and therefore, the triangles so obtained are similar to ones having $n<8$.

Case 2, n = even power of odd number. For example, let $n=9$, $a=3p$, where p is even. Then $a^2/n=p^2=c+b$ = even number, since p is given even. But $c-b$ is given odd. Hence, the condition is impossible, and no triangle is obtained.

Table I. *The first five members of each independent series of rational-sided right triangles for values of n between 1 and 100. Here, a = short side, b = long side, c = hypothenuse, $n=c-b$.*

a	b	c	a	b	c	a	b	c
$n=1$			$n=2$			$n=8$		
3	4	5	8	15	17	20	21	29
5	12	13	12	35	37	28	45	53
7	24	25	16	63	65	36	77	85
9	40	41	20	99	101	44	117	125
11	60	61	24	143	145	52	165	173
$n=9$			$n=18$			$n=25$		
33	56	65	48	55	73	65	72	97
39	80	89	60	91	109	85	132	157
51	140	149	84	187	205	95	168	193
57	176	185	96	247	265	105	208	233
69	260	269	120	391	409	115	252	277
$n=32$			$n=49$			$n=50$		
88	105	137	119	120	169	140	171	221
104	153	185	133	156	205	160	231	281
120	209	241	161	240	289	180	299	349
136	273	305	175	288	337	220	459	509
152	345	377	189	340	389	240	551	601
$n=72$			$n=81$			$n=98$		
204	253	325	207	224	305	252	275	373
228	325	397	225	272	353	280	351	449
276	493	565	261	380	461	308	435	533
300	589	661	279	440	521	336	527	625
348	805	877	315	572	653	364	627	725

Table II. *Summary of restrictions upon a and n.**

n	a	p
1	odd	
2	$4p$	any integer
8	$4p$	odd
9	$3p$	odd, with 3 not a factor
18	$12p$	any integer, with 3 not a factor
25	$5p$	odd, with 5 not a factor
32	$8p$	odd
49	$7p$	odd, with 7 not a factor
50	$20p$	any integer, with 5 not a factor
72	$12p$	odd, with 3 not a factor
81	$9p$	odd, with 3 not a factor
98	$28p$	any integer, with 7 not a factor

* If n be any other number between 1 and 100, the triangles so obtained will have sides that are multiples of the sides of some triangle contained in one of the foregoing series.

Table III. *Some three-dimensional combinations.*

x	y	z	r	x	y	z	r
1	2	2	3	4	5	20	21
1	4	8	9	5	6	30	31
2	3	6	7	5	12	84	85
2	5	14	15	6	6	7	11
2	6	9	11	6	10	15	19
2	10	11	15	8	9	12	17
3	4	12	13	9	12	20	25
4	4	7	9	12	16	21	29

But, if we now let p be any odd number not containing 3 as a factor, then $(c+b)$ is an odd number. Since c and b differ by 9, their only common factor can be 3, in which case their sum p^2 must contain the factor 3. But this is excluded by the condition imposed upon p. Therefore, they can have no common factor, and the triangles so obtained are new.

Case 3, $n=2\times$square of an odd number. For example, let $n=18$, $a=6p$, where p is an odd number. Then $a^2/n=2p^2=c+b=2b+18$, or $p^2=b+9=$odd number. Therefore, b must be even, and since $(c-b)$ is given even, so must c. Therefore, a, b, c may each be divided by 2 (at least), or the triangles so obtained are similar to ones having some smaller value of n.

Now, let p be an even number not containing 3 as a factor. Then b and c must each be odd, and since they differ by 18, their only common factor must be 3. But this is excluded by the condition imposed upon p. Therefore, the triangles so obtained are new ones.

Extension to three dimensions. I have not worked out an analysis for the problem to find four rational numbers, x, y, z and r, such that $x^2+y^2+z^2=r^2$. But, by inspection of Table I, many suitable combinations may be found. Let x and y be the sides of some triangle in Table I, such that its hypothenuse is one side of (the same or another) triangle whose other side and hypothenuse will be z and r. For example, let x, $y=9$, 12 be the sides of the triangle whose hypothenuse is 15 (similar to the first triangle in column 1, Table I), and let 15 be one leg of the triangle 15, 20, 25 (the same triangle again), giving $z=20$, $r=25$. Or, let 15 be one leg of the triangle 8, 15, 17, giving $z=8$, $r=17$.

Other combinations can be found by using the identity

$$(np)^2+[n(p+n)]^2+[p(p+n)]^2\equiv[p^2+np+n^2]^2.$$

Table III gives ten possible combinations derived in one of the ways described and six other combinations not found by either of these methods.

Appointment Service

Representatives of departments or of institutions having vacancies are urged to write to the Editor for additional information concerning the physicists whose announcements appear here or in previous issues. *The existence of a vacancy will not be divulged to anyone without the permission of the institution concerned.*

6. M.S., N. C. State College; 5 summers grad. work, Univ. of Chicago. Age 39, married. 3 yr. instr. N. C. State College; 5 yr. asst. prof., 7 yr. assoc. prof., Woman's College, University, N. C. Interested in undergraduate teaching or technical research.

7. A.M., A.B. Princeton; 2 yr. additional grad. work in spectroscopy, Princeton and Columbia. Age 30, unmarried. 4 yr. instr. Univ. of Vermont. Special interest in teaching and in developing demonstration and laboratory experiments.

8. Man, 36, married. 15 yr. teaching experience in two eastern universities. Completing Ph.D. thesis in spectroscopy this year at Cornell. Undergraduate teaching experience: demonstration lectures, premedical physics, optics, atomic physics, astronomy, astrophysics.

9. Ph.D. Univ. of Minnesota; S.B., S.M., M. I. T.; 1 yr. grad. work, Univ. of Iowa. Age 38, married, 2 children. 17 yr. teaching experience in universities, colleges and technical schools, including 10 yr. head of department. Interested in progressive undergraduate and graduate teaching and research, including mathematical physics.

10. M.S., B.S. Louisiana State Univ.; 3 yr. graduate work, Cornell; doctorate almost completed. Research in spectroscopy. Age 28, unmarried. 4 yr. instructor, Louisiana. Special interest in teaching and in developing demonstration and laboratory experiments.

12. Ph.D. Cornell, B.S. Bowdoin College. Age 38, married. 11 yr. teaching in both men's and women's colleges in East and South. Research in electron physics. Special interest in development of demonstration lectures, laboratory experiments and equipment. Glass Blowing.

13. Ph.D. Cornell. Age 31, married, 2 children. 4 yr. college teaching, 5 yr. full-time research in x-rays. Primarily interested in college teaching and research. Hobbies: photography, geology, music.

14. Ph.D. Chicago, B.S. Bradley Polytechnic, with minors in math. and chem. Age 25, married. 4 yr. laboratory and teaching assistant, Chicago. Research, Faraday effect at high frequencies.

15. Ph.D. Iowa State, B.S. in E.E. Minnesota. Age 33, unmarried. 5 yr. sales and research engineer, 4 yr. teaching fellow, physics. Research, effect of gas on metal surfaces used for electron recording, etc. Interested in teaching.

Any member of the American Association of Physics Teachers who is not employed in a capacity that makes use of his training in physics may register for this appointment service and have a "Position Wanted" announcement published without charge.

Available Graduate Appointments and Facilities for Advanced Study

INFORMATION concerning available graduate appointments in physics and facilities for advanced study and research in various colleges and universities will appear in the December, 1937 issue of *The American Physics Teacher*. Heretofore a comprehensive list has appeared annually but conditions at most institutions do not change sufficiently from year to year to justify an annual survey. The lists published in the December, 1935 and February, 1936 issues give information concerning 66 different graduate departments.

APPARATUS, DEMONSTRATIONS AND LABORATORY METHODS

The Electrically Driven Tuning Fork as a Source of Constant Frequency for the Precise Measurement of Short Intervals of Time

R. B. Dow, *School of Chemistry and Physics, The Pennsylvania State College, State College, Pennsylvania*

THE problem of the accurate measurement of small intervals of time is one of the most common and difficult in the physical laboratory. This is due not alone to the cost of suitable equipment for the purpose, but to the physical limitations of many of these timing devices for the purposes of the laboratory. Inasmuch as all physical and chemical laboratories have need for constant-frequency alternating current sources for bridge measurements of electrolytic resistance, capacitance and inductance, any apparatus that is sufficiently flexible to be operated as a frequency source as well as a timing device, without any loss of precision, is doubled in value as a laboratory instrument. For instructional purposes such a clock or frequency source should be portable, easy to adjust for operation, stable under conditions encountered in the elementary laboratory, and of a simple design that can be readily comprehended by the student.

Precise frequency standards fall into one of two classes: those that depend on gravity for the restoring force, such as the pendulum, and those that depend on elasticity, as illustrated by a rod vibrating by magnetostriction, or the natural oscillations of a crystal of quartz. Pendulums are difficult to adjust satisfactorily under most laboratory conditions and for many purposes their frequencies are too low. Magnetostrictive and crystal oscillators, on the other hand, are easy to operate and are the most precise generators of frequency, but their usefulness is limited to frequencies of 1000 cycles/sec. or higher. The most common source of low and intermediate frequencies for laboratory bridge measurements has been the electrically excited tuning fork. Those who are familiar with its operation will recall the usual trouble of heating of coils and contacts when used over long periods of time, and change of frequency when the power output is large. Intrinsically, however, the tuning fork is an ideal generator of low frequency oscillations for, when used in conjunction with a suitable circuit, it is capable of relatively large outputs of power over long periods of time without the limitations that have been mentioned.

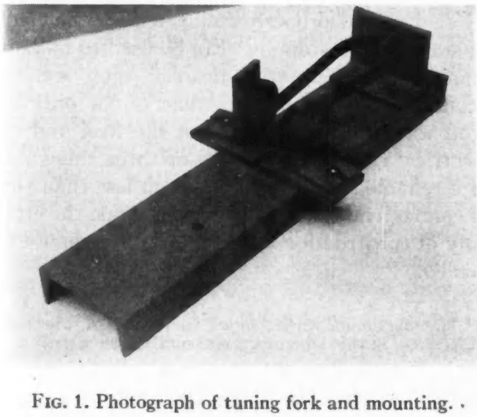

FIG. 1. Photograph of tuning fork and mounting.

A tuning fork, electrically operated and provided with an output amplifier, has been in use in our laboratories as part of the research program of the Pennsylvania Crude Oil Association, and since the apparatus serves the broader purposes of the laboratory successfully, it is the purpose of this paper to describe its design in some detail.

The tuning fork and its mounting (Fig. 1) require little explanation. The fork was shaped from a bar of Elinvar,[1] which is characterized by low temperature coefficients of expansion and

[1] Obtained from the R. G. Ferner Co., New York, N. Y., who import it from the Guillaume Laboratories, Paris. The bar was heated to a cherry red at the section to be bent and then shaped to proper size by bending around an iron pipe; a hammer can be used for the latter operation safely.

elasticity, of length 20 in., width $\frac{1}{2}$ in., and thickness $\frac{3}{16}$ in. The completed fork has a frequency of approximately 60 cycles/sec., the exact value of which can be found by calibration in any of the usual ways. Two 1000-ohm radio headphones are so mounted on the base of the fork that they can be adjusted to any position on the outer sides of the prongs. The magnets of these headphones provide the driving and pickup coils which in turn are part of the vacuum tube circuit shown in Fig. 2.

The oscillating circuit[2] comprises the coils of the magnets, the 79 tube which serves as two tubes, and the radio transformer A, General Radio manufacture, type 585 H, of ratio 1 : 3.5. In operation, the fork is first plucked, then the pickup coil transmits the signals to the grid of the 79 tube while the driving coil in the plate circuit of this tube continues to keep the fork in vibration. The output from the oscillating circuit is amplified by a 77 tube, which delivers a large audio-frequency output voltage for a relatively small input voltage, and then feeds into a standard class A amplifier of push-pull type which employs two 89 tubes. The push-pull amplifier enables the 89 tubes to give more than double the output of one tube, normally about 3.5 watts, with a reduction in distortion. General Radio transformers 541A and 541B were used as transformers *B* and *C*, respectively, in the push pull unit. A 1-μf condenser across the primary of the input transformer serves to eliminate harmonics. The power obtainable from the output side of the circuit depends on the "B" and "C" voltages, although they are not critical. It has been found convenient in this laboratory to obtain these voltages from a standard rectifying circuit. For a normal power output exceeding 3 watts, plate voltages of 105, 185 and 250 have been used with grid bias of -16.5 and -4.5 volts, as shown in Fig. 2.

This method of tuning fork excitation and amplification has obvious advantages. The impressed frequency of the fork controls the oscillations of the circuit, making it unnecessary

[2] I am indebted to Dr. John M. Ide for much helpful information concerning the details of the timing circuit.

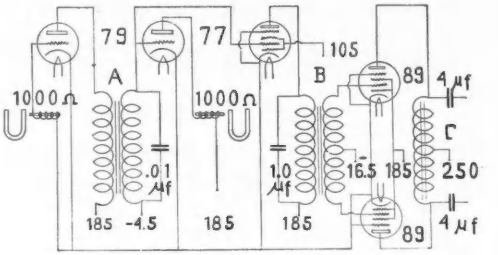

FIG. 2. Vacuum tube circuit.

to thermostat the tubes; the fork itself vibrates with so nearly constant frequency that no precautions need be taken with it except in cases where the highest precision is required. Over a period of 24 hours the average variation of frequency per hour has been found to be about[3] 0.002 percent. The circuit is remarkably stable; no particular precautions need be taken to protect it from the ordinary disturbances about the laboratory. Since there are no "make" and "break" contacts, continuous operation is assured at full power output. While no parasitic disturbances have interfered with the operation of the apparatus as described, it may be advantageous in some cases to shield the 89 tubes and ground both the shields and the cases of the transformers.

As a source of 60-cycle alternating current, the output in excess of 3 watts is sufficient for the simultaneous operation of several electrical bridges. With a synchronous motor, such as the Warren Telechron, the apparatus can be used in many ways as a timing device. For example, a self-starting Telechron motor when operated by relays, and properly calibrated for the errors of starting and stopping, can be used to measure time intervals to the nearest 1/60 sec., an accuracy about 10 times that of an ordinary stop watch. Since the cost of the fork and the electrical circuit is only two or three times that of a reliable stopwatch and much less than that of commercial electrically-driven forks, the economy of construction in the laboratory cannot be denied.

[3] The maximum variation of frequency of the commercial a.c. in this laboratory is about 0.2 percent.

An Intermittent Air-Blast Method of Exciting Transverse Vibrations in a Bar

B. W. CURRIE, *Department of Physics, University of Saskatchewan, Saskatoon, Canada*

THE following method for demonstrating resonance and beats, and for verifying the laws governing the transverse vibrations of bars or reeds, fixed at one end, apparently is not recorded in the literature on the subject that is conveniently available, although its simplicity and ease of application suggests that it frequently has been used by others. It consists of exciting transverse vibrations in a bar by an intermittent blast of air.

A jet of air from the compressed air main is arranged so as to strike the face of the bar at the free end. A disk with a number of holes or slots, evenly spaced on one of the circumferences, is rotated between the bar and the jet by a motor-rotator with a friction drive, so that the air blast can strike the bar only through the openings. By varying the speed of the rotator until the number of impulses from the air blast is about equal to the natural frequency of the bar, or to a submultiple of the natural frequency, the bar is set in vibration. By adjusting the speed until the bar is vibrating without beats, and then using the revolution counter on the rotator to measure the number of revolutions made by the disk in a convenient interval of time, say 5 min., the frequency of the bar can be easily computed.

With this method of excitation all the ordinary solids (including glass and wood) that can be cut into bars may be used. The width of a bar should be about 1 cm and the thickness and length, such values that the frequency is under 100 vib/sec. For larger widths and higher frequencies it is difficult to get sufficient energy from the air blast to excite the vibrations. To secure the maximum energy the angle subtended at the center of the disk by each opening should be equal to the angle subtended by the space between successive openings. Various numbers of openings (2, 4, 6 and 8 for frequencies from values just too large to be counted visually to about 100 vib/sec.), may be cut on different circumferences on the same disk, the sets with the larger numbers of openings being used with the higher frequencies so that the speed of the rotator need not be excessive.

Beats are easier to demonstrate if the size of the openings is from one-quarter to one-half of the aforementioned value. With openings of this size submultiples of the true frequency are likely to be measured unless the speed of the rotator is increased until the resonance point corresponding to the highest speed is found. An alternative method is to find two successive resonance points and use these to compute the true frequency.

The accuracy of the results is dependent to a considerable extent on the steadiness of the voltage supplied to the rotator and on the quality of the friction drive. Generally there is not more than 1-percent variation in the number of revolutions on successive timings over 5-min. intervals. If any difficulty is experienced in getting perfect unison between the impulses of the air blast and the vibrations of the bar, the speed of rotation is adjusted until the number of beats can be counted. This number is either added to or subtracted from (depending on whether the speed of rotation is below or above that required for resonance) the number of impulses on the bar in computing the frequency.

For demonstrating resonance and beats a beam of light is reflected to a screen from a small mirror waxed to the free end of the bar, so that the motion of the bar is indicated by the spot of light on the screen. In addition to the condition for resonance various beat frequencies can be shown simply by altering the speed of the rotator. The demonstration is one that beginners can understand easily, and as a result it proves to be an effective introduction to problems of this nature.

This method also may be used by an advanced laboratory class to verify the relation

$$n \propto k/l^2(E/d)^{\frac{1}{2}},$$

where n is the frequency of transverse vibration of a bar fixed at one end; k is the radius of gyration of the cross section, normal to the length of bar, referred to the line in the neutral surface; E is Young's modulus; l is the length of the free portion; and d is the density. The frequencies corresponding to at least two

different free lengths of the given bar are measured, and shown to vary inversely as l^2. Similarly, by first using two bars of the same length and the same material but of different thicknesses, and then two bars of the same length and the same thickness but of different materials, n is shown to vary directly as k and $(E/d)^{\frac{1}{2}}$, respectively. Also, a steel bar about 60 cm long and 1 mm thick is made to vibrate with overtones and their frequencies are shown to be inharmonics of the fundamental frequency. At the same time the distances between the nodes are measured, and are compared with the theoretical values.[1] The method is particularly convenient for determining Young's modulus of wood. The agreement between this result and that obtained by deflection experiments on the same wood is close.

[1] A. B. Wood, *Sound* (1930), p. 113.

Double Bulb Neon Oscillograph

JAMES F. KOEHLER, *Department of Physics, Smith College, Northampton, Massachusetts*

PROBABLY the most satisfactory method of demonstrating the phenomena of current lag or lead in an alternating current circuit is the use of the electronic switch circuit in combination with a cathode ray oscillograph, whereby the two wave forms under comparison are viewed simultaneously. But in an introductory course this demonstration is less successful since considerable explanation is required to expose what is going on within the boxed apparatus; and, because the cost is still rather high, the apparatus is not everywhere available. Nor is complete satisfaction met in methods that employ Lissajous figures, such as the electromagnetic oscillograph, or the direct use of the two pairs of plates in a cathode ray tube, because of the necessary interpretation of the figures.

A simpler, inexpensive solution has been found in a modification of the usual rotating neon lamp by adding a second lamp so that two wave forms are simultaneously seen, the one above the other, but with a common time scale. This requires only the construction of a rotating head with contact brushes, and its attachment to the electrical or hand-turned rotator found in every laboratory. The rotating head (Fig. 1) carries two 2-w neon lamps of a type (such as the General Electric) in which the inter-electrode division appears as a diameter when the bulb is viewed end-on. This division line is adjusted to be in the plane of rotation. Standard light sockets are attached by means of threaded, 3-in. long pipes to a partially hollowed 7/8-in. brass rod, and the leads are brought out from the hollowed portion through inclined holes to the four slip rings. The rings are fitted tightly over a Bakelite bushing which contains four external grooves for passing the far leads under the near rings. The bottom of the central rod is turned down to fit the rotator. A counterweight is screwed onto a threaded rod projecting on the opposite side from the bulbs and is held in the balancing position with a lock nut. The brushes are attached with insulation to a brass post (Fig. 1) which is held by a set screw in a hole in the rotator frame, or may be simply supported in a clamp stand.

In operation one neon bulb B_1 is connected directly with the alternating current power supply and, when rotated at a synchronous speed of about 480 rev./min. or faster, displays the familiar flat-topped wave form. The potential on the second neon bulb B_2 is the IR-drop over a 60-w blackened Mazda lamp M which, by suitable switches, is connected in series with either a 30-μf bank of condensers C in steps of 2 μf, or a 0.6 h (0.5 amp.) variable choke L, or both of these in series, or both in parallel, or simply the alternating current power line. The

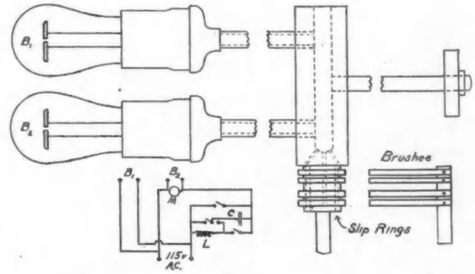

FIG. 1. Diagram of rotating head, brushes and circuit.

maximum phase shift obtainable in B_2 with capacitance or inductance alone and 60-cycle current is about 75°, since further increase of inductance or decrease of capacitance reduces the current in the Mazda lamp to a point where the IR drop is not sufficient to light the neon bulb. The minimum shift is of course governed by the total capacitance available, or the ability to reduce the inductance to zero. The series resonant circuit is readily demonstrable, and in the parallel filter circuit the neon lamp is extinguished as the phase angle passes through zero. In all cases the difference between the two wave forms is easily apparent.

Incidentally, in the circuit shown, if the blackened Mazda lamp is replaced with a clear 40-w lamp and another 40-w lamp in series with a 200-ohm resistor is substituted for the first neon bulb, the circuit can be used independently of the oscillograph to show the ohmage equivalence of inductance or capacitance, since when the impedance of either of the latter is made equal to 200 ohms, the two lamps are of equal brilliance; and the current-amplitude behavior in series and parallel resonance can also be quickly displayed.

The double neon bulb rotator also renders more striking the demonstration of rectification, both half- and full-wave, with and without filters; for the one bulb is constantly displaying the alternating current wave form for comparison. The voltage on bulb B_2 can be obtained from the usual power supply circuit of radio sets, using an '80 tube, a 700-v center-tapped transformer secondary, two 30-h chokes, two 4-μf electrolytic condensers, a 3000-ohm bleeder resistance, and suitable switches.

Some Demonstrations of Spinning Tops and Gyroscopes

ROBERT C. COLWELL, *Department of Physics, West Virginia University, Morgantown, West Virginia*

A SPINNING gyroscope will, when given a rotation about an axis perpendicular to its own spin axis, precess about a third axis perpendicular to the other two. This phenomenon is in strict accord with Newton's laws of dynamics and should be explained from the physical principles involved. It is usually taught in terms of a combination of two vectors into a third vector. This is correct mathematically but the method never gives the student insight into the real cause of the precession. The references given in footnote 1 explain carefully and accurately the physical reasons for precession. There exist a number of useful and well-known standard demonstrations, such as the bicycle wheel with loaded rim, the miniature monorail car, the double top, etc., but the present paper will be confined to some demonstrations that are not used so generally.

When a gyroscope is supported at one end it will have a precession in a certain direction, say clockwise. If the point of support is changed to the opposite end, then the precession will change and be directed anticlockwise. Gray[2] has invented a top based upon this fact, which will walk along two parallel horizontal wires when the wires are rocked back and forth. If the two parallel wires are arranged as an inclined plane, the top will walk down it even when the two wires are not rocked. These wires may be

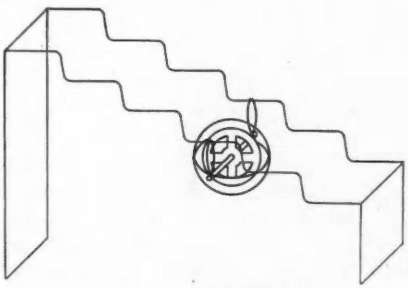

FIG. 1. A walking top.

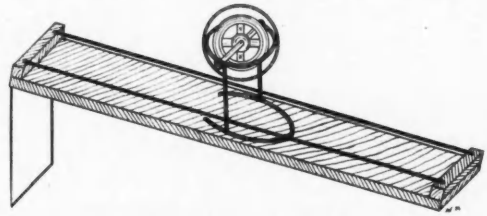

FIG. 2. Second form of walking top.

[1] Gray, *Gyrostatics and Rotational Motion* (1918), Chap. 3, p. 62; Crabtree, *Spinning Tops* (1909), Chap. 8, p. 109; Spinney, *A Textbook of Physics* (1931), pp. 73–75.

[2] Gray, ibid., p. 30.

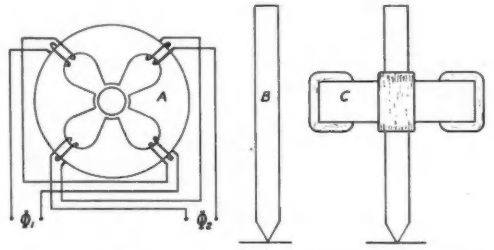

FIG. 3. A, electromagnetic two-phase spinner; B, the spinning copper rod, height, 8 in., diameter 0.5 in.; C, the rod inserted in the spinner.

arranged in steps (Fig. 1) and the top descends as though it were conscious of what it is doing.

It is also possible to make a top descend an inclined board provided there are two parallel wires which start and stop the precession. Such an arrangement is shown in Fig. 2. As the rotation of the top decreases, the precession becomes faster so that toward the end the top fairly runs down the board.

The conical and gyroscopic tops sold as toys are set in rotation by means of a string. The rotational speed seldom exceeds 4000 rev.·min.$^{-1}$. Such tops must have a low center of gravity or they will not stand up for any length of time. If the top is in the form of a cylinder long and thin like a lead pencil it will not remain upright unless it has a very high rotational speed. Such speeds may be attained by using certain electrical devices. The ordinary induction motor has two phases 90° apart and runs on the usual 60-cycle current so that the armature has 3600 rev.·min.$^{-1}$. Now radio oscillations are much higher. An Alexanderson two-phase alternator of the type used in radio was designed[3] to give 120,000 oscillations per minute. Its field was applied to a copper rod which formed the rotor. In this way a speed of 100,000 rev.·min.$^{-1}$ was given to a rod about the size and shape of a lead pencil (Fig. 3). The rod rotated like a top in a vertical position. However, as soon as the field was withdrawn, the friction of the air rapidly slowed down the rotation and the rod soon fell over. With the high speed methods developed by Beams,[4] it should be possible to spin a knitting needle in a vacuum.

At the present time it is possible to obtain

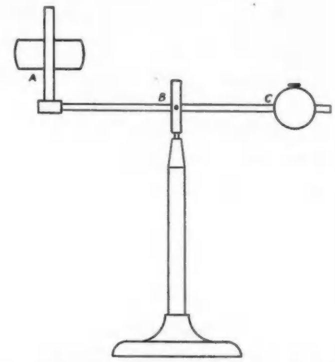

FIG. 4. (left) A, copper disk 2 in. in diameter, 1 in. thick; B, high-speed bearing; C, india rubber ball.
FIG. 5. (right) A, the gyroscopic top spinning in a stable position; B, gimbal bearing; C, counterweight.

commercial ball bearings that will stand a speed of 50,000 rev.·min.$^{-1}$. Such a bearing permits the design of a top with a very long spindle. The one shown in Fig. 4 is 10 in. over all. This top can be spun at 50,000 rev.·min.$^{-1}$ either with the rotating magnetic field or, more conveniently, with an electric motor (the gyro-spinner). The 1-in. india rubber ball on the end of the top increases the friction with the table and helps to keep the top in a vertical position. It should be pointed out that these high speed tops have very large rim speeds so that they should never be run without protective shields.

The gyroscope ordinarily used to demonstrate precession has two degrees of freedom about its point of support. It can be improved by placing a gimbal bearing at the point of support, thus giving three degrees of freedom to the gyroscope (Fig. 5). Such an instrument may be used to demonstrate the difference between static and dynamic stability. When the gyroscope is not spinning, the center of gravity is at the lowest possible position with the top A hanging below the rod BC. If the rod BC is rotated in the gimbal bearing at B so as to raise the top A to the highest possible position, it will be statically unstable. However, if the top is spun rapidly with an electric motor, it will remain stable with the center of gravity at the highest possible position. In order for this to take place, precession must occur, so that the top as it slows down will precess and gradually turn over to its stable position for static equilibrium.

[3] Colwell and Hall, R. S. I. **7**, 153 (1936); Science **83**, 289 (1936).
[4] Beams and Pickles, R. S. I. **6**, 299 (1936).

A Mechanical Vibrator for Demonstrating Standing Waves

WILFRID J. JACKSON AND FRANK R. PRATT, *N. J. C., Rutgers University, New Brunswick, New Jersey*

VARIOUS devices, such as electrically driven tuning forks and electromagnetically controlled vibrators, have been used to put strings under tension into vibration and to demonstrate vibrations that produce the partial tones discovered by Nobel and first recorded by Wallis.[1] The best known experiment of this kind is that by Melde.[2] Recently a device has been described for audibly demonstrating the partial tones in a vibrating string.[3]

The mechanical vibrator described in this paper has advantages over the tuning fork because of its rugged construction. The apparatus has some features not found in a similar device described by Pohl.[4] The vibrator consists of a spring-steel strip S, Fig. 1, clamped firmly at one end and resting on a brass eccentric E, 4.5 cm in diameter with 0.4 cm offset. To help reduce the wear a hardened steel sleeve is shrunk on the eccentric and a fiber tip F is fixed to the steel strip S at the point of contact. The eccentric together with a counterweight and pulley are fastened rigidly to the motor-driven shaft M which is mounted on ball-bearings. The pulley is 3.9 cm in diameter and the over-all length of the shaft is 12.3 cm.

Fig. 2 shows the device in operation. The tension in the string attached to the steel strip is produced by a spring balance reading to 6 kg. This balance is mounted in a brass frame and the tension in the string is varied by means of a screw and crank. The vibrator can be made to vibrate with three different periods as the pulley on the apparatus and the intermediate pulley on the 1800-rev./min. motor have the same diameter. To make the string more visible a board painted dull black is placed behind the string with the ends of the board resting on the mountings of the spring balance and of the vibrator. These mountings are clamped to the lecture table 2 m apart or at any other desired distance. The loops shown in Fig. 2 are about 5 cm wide and, therefore, easily visible in all parts of the ordinary lecture room. In the present arrangement the string which has a line density of 0.058 $g \cdot cm^{-1}$ can be made to vibrate in from 1 to 5 segments. Since the adjustments of length, period of vibration and tension can be made readily, the laws of vibrating strings may also be tested quantitatively before the class.

The authors wish to express their thanks to Mr. Howard I. Pratt who did the machine work on the eccentric.

[1] Phil. Trans. **12**, 839 (1677).
[2] Pogg. Ann. **109**, 192 (1859); **111**, 513 (1860).
[3] Urquhart, Am. Phys. Teacher **2**, 29 (1934).
[4] *Mechanik und Akustik* (Springer, 1930).

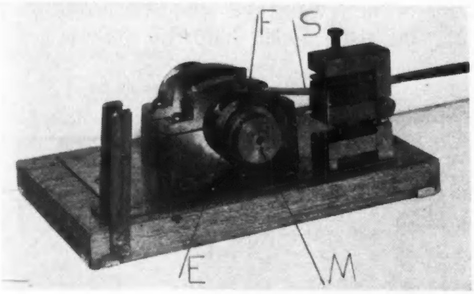

FIG. 1. (above) Photograph of mechanical vibrator.

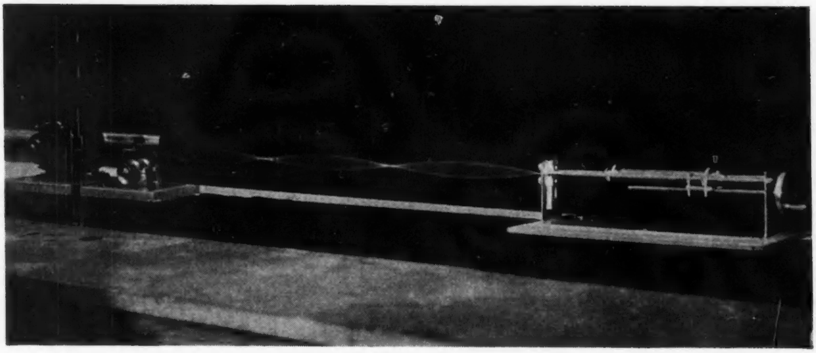

FIG. 2. (right) Photograph of assembled device in operation.

Determination of the Speed of Sound by the Fizeau Toothed Wheel Method

HAROLD K. SCHILLING, *Department of Physics, Union College, Lincoln, Nebraska*

THE first direct demonstration of the fact that light is not propagated infinitely fast was Fizeau's measurement of the speed of light by means of a toothed wheel. Students are usually very much interested in it—both because of its historical importance and because it appears to them as being peculiarly ingenious. It would seem justifiable therefore and even desirable to include such an experiment in a laboratory course for beginners. This can be done readily by adapting Fizeau's method to the measurement of the speed of sound.

In our apparatus (Fig. 1) we make no attempt to focus the sound, as did Fizeau. Hence we use no lenses. Nor do we need a partial reflector at the source because our source is mounted directly in front of the toothed wheel and the sound after reflection at M, instead of returning by the same path, is received at a different point of the wheel. The source S, a Galton whistle, is enclosed in a small box D lined with balsam wool. The receiver is a sensitive flame at F. The toothed wheel W is made of pressed wood. We have wheels of different sizes, the one used most often being 62 cm in diameter and having 10 teeth. It is mounted on the shaft of a variable speed motor, which is itself mounted on top of the box B. The sound enters this box at A_1, is reflected at M, and emerges through aperture A_2. The box B is telescoping, each of the two sections being about 1.5 m long. The distance the sound travels to and fro can therefore be varied up to maximum of approximately 6 m. As shown in Fig. 1*b*, the inner, sliding section can be reversed so that the effective length of the box may be made as small as desired. The wheel is partially enclosed by a shield C; this minimizes effectively the air currents near the sensitive flame. Fig. 2 shows the aperture end of the apparatus. The dotted line d indicates the outline of box B. Hole H_1 in shield C allows the use of a revolution counter or tachometer. Openings H_2 and H_3, in the shield and wheel, respectively, and equidistant from the center of the wheel, permit the use of a phototube counter in determining the wheel's frequency of rotation. The two apertures A_1 and A_2 are cut from an annulus concentric with the wheel. Box D containing the whistle is placed over aperture A_1. Either half a or b of A_2 can be covered so that the effective receiving aperture is of the same size as A_1. This provides for two different angular distances between the apertures and consequently for the use of wheels with different numbers and spacings of teeth.

If the wheel chosen is such that both apertures are either open or closed simultaneously, as indicated by Fig. 3*a*, we shall have the equivalent of Fizeau's single-aperture arrangement, and the the theory of Fizeau's experiment may be applied here directly.[1]

If the wheel is stationary in the position indicated in the diagram, a continuous train of sound waves will enter A_1 and emerge through A_2, producing on the receiver a maximum effect, of intensity I_0. When, however, the wheel is rotating the sound will be intermittent and therefore, the effective intensity less. If the speed of sound were infinite, then, for all speeds of the wheel, all the sound entering the box would emerge from it and the effective intensity I would be determined only by the relative

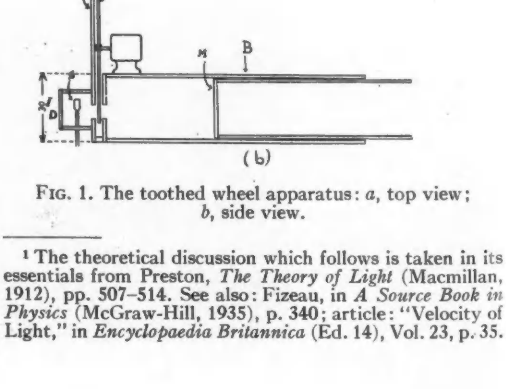

FIG. 1. The toothed wheel apparatus: *a*, top view; *b*, side view.

[1] The theoretical discussion which follows is taken in its essentials from Preston, *The Theory of Light* (Macmillan, 1912), pp. 507–514. See also: Fizeau, in *A Source Book in Physics* (McGraw-Hill, 1935), p. 340; article: "Velocity of Light," in *Encyclopaedia Britannica* (Ed. 14), Vol. 23, p. 35.

magnitudes of β and α, the angular widths of the teeth and of the spaces between them, respectively. It would be $I=I_0\alpha/(\alpha+\beta)$. Since, however, the speed of sound is finite, the effective intensity will be still less because some of the sound will in general be intercepted by a tooth at A_2. If the wheel rotates through an angle ϵ while the sound travels the route A_1MA_2 (Fig. 1) the available aperture at A_2 will be $\alpha-\epsilon$, and the effective intensity will be

$$I=I_0(\alpha-\epsilon)/(\alpha+\beta). \qquad (1)$$

The angle ϵ equals $2\pi nT$, where n is the number of revolutions of the wheel per second and T, the time it takes the sound to travel to the reflector and back again. Hence Eq. (1) becomes $I=I_0(\alpha-2\pi nT)/(\alpha+\beta)$. Since for a given length of box and a given wheel the quantities α, β, T are constant we write

$$I=I_0(k_1-k_2n), \qquad (2)$$

where $k_1=\alpha/(\alpha+\beta)$, $k_2=2\pi T/(\alpha+\beta)$.

There are three possibilities as to the relations between α and β: we may construct our wheels so that $\alpha=\beta$, $\alpha<\beta$, or $\alpha>\beta$.

If $\alpha=\beta$, then $k_1=\frac{1}{2}$ and $k_2=\pi T/\alpha$. When $n=0$, the effective intensity will be maximum and equal to $I=\frac{1}{2}I_0$. As n increases, I decreases linearly (Fig. 3*b*) and becomes equal to zero when

$$n=N_1=k_1/k_2=\alpha/2\pi T, \qquad (3)$$

where N_1 refers to the frequency of rotation of the wheel for "first eclipse." The broken line $M_1E_1M_2E_2$ in Fig. 3*b* shows the further variation of I for higher values of n.

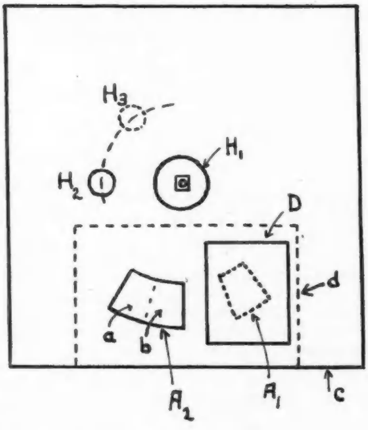

FIG. 2. Aperture end of toothed wheel apparatus.

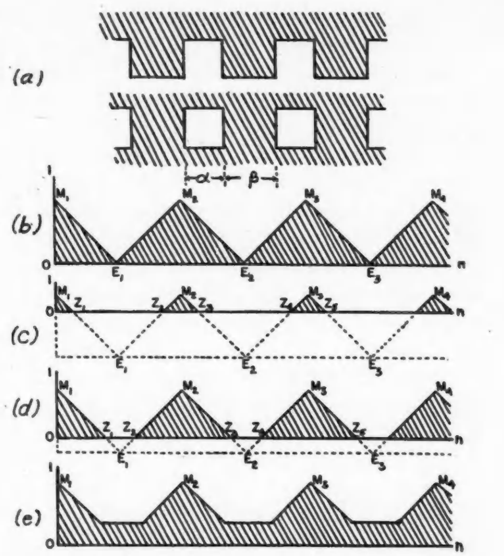

FIG. 3. *a*, Schematic diagram showing assembly of wheel and apertures equivalent to Fizeau's single aperture arrangement; *b*, curve showing relation of intensity of sound to frequency of rotation of wheel, $\alpha=\beta$; *c*, intensity-frequency relation, β being slightly larger than α; *d*, intensity-frequency relation, $\beta\gg\alpha$; *e*, intensity-frequency relation, $\alpha>\beta$.

When $\alpha<\beta$ there will be a range of frequencies for which there is extinction. Eclipse occurs first when $\epsilon=\alpha$ or $n=\alpha/2\pi T$ (Z_1 in Fig. 3*c*) and persists until $\epsilon=\beta$ or $n=\beta/2\pi T$ (Z_2 in Fig. 3*c*).

The situation for $\alpha>\beta$ is illustrated by Fig. 3*e*.

The frequencies for points E_1 on all the curves of Fig. 3 are given by $N_1=(\alpha+\beta)/4\pi T$. If the wheel has m teeth, then $m(\alpha+\beta)=2\pi$. Hence, $N_1=\frac{1}{2}mT$. Also, $T=2D/v=2(l^2+L^2)^{\frac{1}{2}}/v$, where v is the speed of sound, $2D$ is the total distance traversed[2] by the sound in the box, l is half the distance between apertures, and L is the distance from the wheel to the reflector. Therefore

$$N_1=v/4mD. \qquad (4)$$

It will not be necessary to develop the equations for higher orders of minima or for maxima. The speed of sound may be calculated from Eq. (4) in terms of N_1, m, D. The fact that these quantities are all variable in this apparatus offers a great pedagogic advantage over the optical experiment.

[2] There has been no difficulty due to reflection at the walls of the box.

When using a sensitive flame as detector it is best always to have $\alpha<\beta$. When working with maxima of intensity quantitatively, β should be at least two or three times larger than α. In that case the relation between n and I is given by a curve such as that of Fig. 3*c*, there being large ranges of frequencies and speeds of the wheel for which no sound at all reaches the flame, and only very narrow ranges for which sound is transmitted; the maxima can then be located more easily since they lie within these narrow ranges which are sharply distinguishable from the ranges of extinction. When working with minima, β should be only slightly larger than α. The situation in that case is depicted by Fig. 3*d*, there being wide ranges of transmission and narrow ranges of extinction. Eq. (4), and similar equations for higher orders of minima, can then be used with data taken at the middle of these narrow ranges. When $\alpha=\beta$ these narrow ranges are contracted to points, that is, to a single speed of the wheel, and it becomes impossible in practise to find the minima. When $\alpha>\beta$ there is transmission of sound for all speeds of the wheel, there are no eclipses, and it is impossible with the flame to distinguish between the maxima and minima.

An interesting variant of the experiment is to space the teeth of the wheel or the apertures in such a manner than when one aperture is either partially or totally open the other is completely closed. In that case there will be total eclipse whenever the wheel is stationary, a case impossible optically.

A setting for eclipse or maximum intensity can be obtained experimentally by first giving the wheel any convenient speed and then adjusting the box to find the proper distance D for which the flame does not flare, or *vice versa*.

TABLE I. *Typical results for first eclipse.*

N_1	D cm	t°C	v_t	$0.607t$	v_0 m/sec.
2.17	211	26	366	15.8	340
2.08	209	22	348	13.3	335
2.08	207	22	347	13.3	334
2.13	207	22	352	13.3	339
3.03	142	21.5	344	13.0	331
1.54	278	22.5	342	13.7	329
1.64	261	23	342	13.9	329
4.00	105	22.5	336	13.7	322

Mean 332.4 m/sec.

The typical results shown in Table I were obtained by a student for first eclipse for various values of N and D with a wheel having 20 teeth, α being approximately $\frac{4}{5}\beta$, and $2l$ being 16 cm. To save space the readings for L are omitted. It will be seen that the mean value of the speed reduced to 0°C is within 0.5 percent of the accepted value[3] for open air.

It should be pointed out, also, that the apparatus is well adapted to use in the lecture room. It is small enough to be portable, can be manipulated with ease, and the effects can be observed simultaneously by a large number of students.

In conclusion the writer wishes to express his appreciation and thanks for the intelligent help given and faithful work done by his assistants Mr. Wm. Whitson and Mr. Henry Brown during the development of this apparatus.

[3] Various values have been found for the speed of sound in air. For present purposes it may be proper to accept the value $v=331.5$ m/sec. at 0°C.

Reprints of Survey Articles for Class Use

Reprints of the following survey articles which have appeared in various issues of *The American Physics Teacher* may be obtained at cost from the Editor, Pupin Physics Laboratories, Columbia University, New York, N. Y.:

R. Bowling Barnes and Lyman G. Bonner, *The Early History and the Methods of Infrared Spectroscopy*, 60 cts. for 6 copies.
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Reprints of the articles by W. V. Houston, G. P. Harnwell, Walker Bleakney and L. L. Nettleton are no longer available.

A Free-Fall Apparatus Which Uses Photographic Recording

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TO obtain a permanent time-distance record of a freely falling body is not a simple problem. One very satisfactory method which makes use of an accurately timed spark discharge through paper has been described by L. Behr and F. W. Reynolds.[1] Another method is the photographic one in which intermittent flashes of light produce a record on a light-sensitive material attached to the falling body. Various modifications of this method have been described by E. Langton and E. Tyler.[2] The apparatus herein described employes the photographic method. The apparatus has been found to work admirably in the elementary laboratory and its ease of construction places it within the range of the small physics shop. Mr. Harold Warner, an undergraduate student in physics, made the apparatus now in use in this laboratory.

The box in which the body falls is formed from four strips of strong lightweight wood. Each strip is 85 cm long, the widths being chosen so that the inside cross section of the completed box is a square with 5 cm edges. Before the strips are fastened together their inside surfaces are painted black. The joints must be light tight. The bottom of the box is a hardwood block *e* (Fig. 1) to which the supporting rod is fastened, the top nut on the rod being countersunk. Above *e* there is a thin block *d* which covers the nut on the supporting rod and serves as a base for a layer *c* of cork or other shock absorbing material. The box is mounted on a medium-heavy tripod base which is fitted with leveling screws.

A wooden cap, fitting light tight, covers the top of the box. Two wooden or metal strips *a*–*a* are fastened to the under side of the cap to form a groove into which the upper end of the free-fall body fits. This groove serves to keep the body facing in the proper direction. The device *D* fastened to the top of the cap is made from a short piece of brass rod (Figs. 1 and 2). The thread which supports the free-fall body passes up through a small hole drilled along the axis of *D* and fastens around the pins *f*. The body is dropped by cutting the string at *g*.

The collimating device *A* consists of a brass tube 2 cm in diameter and 6 cm long; each end appears as in Fig. 2. Each slit is 0.7×0.05 cm. The two are carefully adjusted for parallelism. The easiest method of forming a slit is to use two pieces of sheet brass each of which is large enough to cover half the cross section of the tube. One edge of each piece is beveled and the two are then soldered onto the end of the tube to form the slit. Thin copper foil is soldered over the ends of the slit to give it the proper length.

The arc *E* consists of $\frac{5}{16}$-in. carbons held by a frame made of $1\times\frac{1}{8}$-in. strap iron. At least one of the carbons must be insulated from the iron support in a way like that shown in Fig. 2, where *n* designates the carbon, *h* is the iron support, *i* is a brass bushing with a brass nut *l*, *m* is a hard rubber or fiber insulating washer, and *k* is a spring strip which holds the carbon in place. When the arc is fastened to the box great care must be taken to align the tip of the upper horizontal carbon with the collimating slits. The carbons should be provided with insulating handles and with leads to binding posts fastened at some convenient point on the box.

A light trap *L* covers the opening *b*. The latter is just large enough to allow all of the light which passes the collimating slits to enter *L*.

The timing disk (Fig. 2) is a circular disk of sheet metal 15 cm in diameter and 0.2 cm thick, made to fasten to a shaft which has an angular speed of at least 1800 rev./min., the speed being known or susceptible of accurate measurement. In use the disk is placed so that, as it revolves, openings *o*, each of which is 1.5 cm long, pass in front of the slits to give the recording light flashes. If time intervals are to be uniform, corresponding edges of the openings *o* must be diametrically opposite.

A photograph of the free-fall body with record strip inserted is shown in Fig. 3(*a*). The upper part of this body is made from sheet aluminum $\frac{1}{32}$ in. thick, the edges being turned over to form

[1] "Free-Fall Apparatus," J. O. S. A. **13**, 216 (1926).
[2] "Photographic Time Registration on a Falling Plate in an Experimental Determination of *g*," Phil. Mag. (7) **18**, 352 (1934).

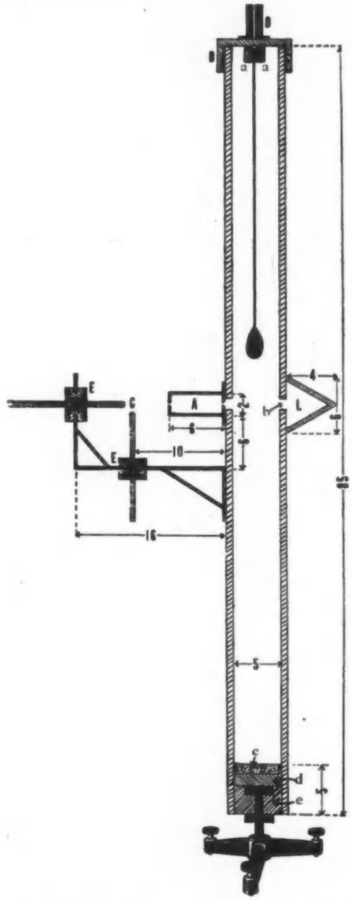

FIG. 1. Diagram of free-fall apparatus. The dimensions are in centimeters.

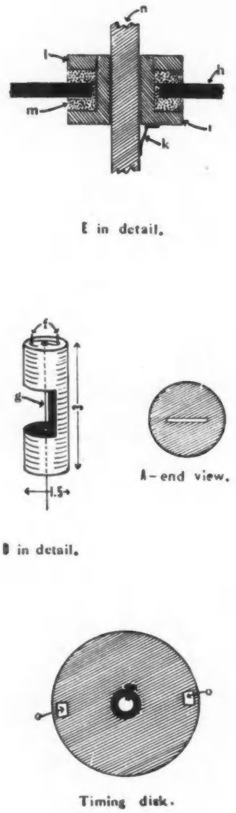

FIG. 2. Details of arc E, support D, collimating slit A and timing disk.

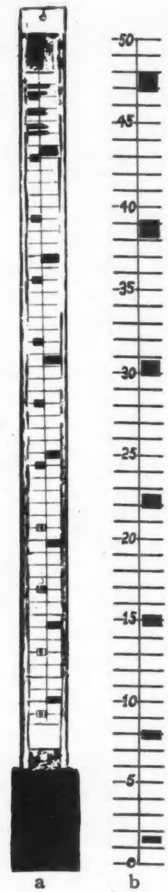

FIG. 3. (a) Photograph of free-fall body with sample record. (b) Line drawing of a record strip.

a holder for a record strip 1.6×30 cm in size. P.M.C. No. 9 bromide photographic paper, normal, has been found satisfactory for the records. The weight at the bottom, to which the upper part is riveted, is 4 cm long, 2 cm wide, 2 cm thick at the thickest point and is made by bending thin sheet brass into the desired shape and filling it with solder or lead. The distribution of mass must be such that the center of gravity of the free-fall body is in the weight at the bottom.

The linear scale on the record strip serves two purposes. It minimizes error that might arise from shrinkage or stretching of the paper during development and it simplifies measurements in that it is only necessary to measure the distance from a flash mark to the nearest division line. A latent image of the scale is formed on the record strip by proper exposure through a master negative just before a record is to be made. The master negative itself is made by photographing some suitable scale.

The record shown in Fig. 3(a) was made with the timing disk attached to the shaft of a synchronous motor rated at 1800 rev./min. on a frequency-controlled circuit. The distance measurements made from the record yielded a value of 973 cm/sec.[2] for the acceleration due to gravity.

An Indicating Lantern Slide Color Mixer

JOHN J. HEILEMANN, *Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pennsylvania*

THE simple color mixer recently described by the author[1] has been improved to permit mixing the colors in any desired proportions and to give a visual indication of the relative quantities of the components used to produce the resultant color. The necessary materials, in addition to the projection lantern, are three small pieces of red, green and blue gelatin filters, a $3\frac{1}{4}\times 4$-in. "aperture slide" consisting of a brass plate containing a 1-in. hole, a 4×5 cm microscope cover glass, a lens of 20 cm focal length, and a plane mirror.

A projection lantern ordinarily is properly adjusted when a real image of the light source, in this case a flat filament, is formed on the objective. In the present arrangement (Fig. 1), the distance b between the source A and the condenser B is decreased so as to cause the image to be formed a centimeter or so in front of the objective. The "aperture slide" C is placed in the slide carrier so that the objective D focuses this aperture on the screen K at G.

Fig. 1 shows the filter. The three pieces of gelatin (Wratten Nos. 61, 29 and 47) are cut in

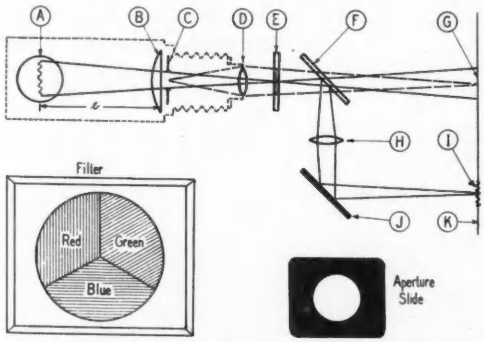

FIG. 1. Arrangement of apparatus, and details of filter and aperture slide.

[1] Am. Phys. Teacher 3, 184 (1935).

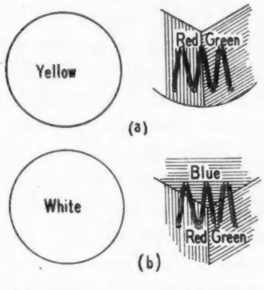

FIG. 2. Appearance of images.

the form of circular sectors whose angles are 120°, fitted together as shown, and bound between cover glasses. If this filter is placed at E, where the real image of the filament will be formed upon it, the image at G will be colored. The relative proportions of the filters in use may be varied by moving the filter slide about in the beam. It is important to have the filter slide and the real image of the filament coincide; otherwise the coloring of the spot G is not uniform.

The position of the filter relative to the axis of the beam is made evident to the audience by projecting its image I on the screen K. The microscope cover glass F is placed in the beam so as to reflect a portion of the light to the side, the mirror J reflects it to the screen, and the lens H is placed so as to focus the image of E on the screen at I. Since the filter and the real image of the filament coincide, the filament is also focused at I. Fig. 2 attempts to indicate the appearance of the images. In (a) the filament is covered partly by the green sector and partly by the red; the resultant is yellow. White is produced as shown in (b). The use of the three colors to approximate any part of the continuous spectrum is strikingly demonstrated by slowly rotating the filter so that the resultant frequency appears to be decreasing or increasing continuously.

THE most essential characteristic of scientific technic is that it proceeds from experiment—NOT FROM TRADITION.—BERTRAND RUSSELL

A Continuously Variable Diaphragm for Use in Spherical Aberration Studies

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IN the theory of geometrical optics, the amount of longitudinal spherical aberration suffered by a ray of light on passing through a thin lens is commonly expressed as a function of the height h of the ray above the principal axis of the lens. In order to facilitate the study of the aberration the diaphragm shown in Fig. 1 was devised.

A V-shaped slot is cut in a rectangular piece of sheet metal and a straight slot of length equal to the diameter of the lens to be studied is cut in an approximately square piece of the same material. Parallel ways are then provided in the latter piece and spaced so that the piece containing the V-shaped slot will slide into them. When the two slots are opposite each other the effect is to form two diamond-shaped apertures at a distance $2h$ apart. The lens is mounted immediately behind the slots so that the two apertures will be situated symmetrically with respect to the principal axis of the lens. The height of the rays above the principal axis may be varied continuously by sliding the rectangular piece in its ways, and when the diaphragm is mounted with the lens on an optical bench provided with a source and screen the amount of longitudinal spherical aberration may be studied as a function of h. If desired a scale and index may be ruled on the sheet metal which will read the height h in convenient units.

Fig. 2 shows typical results for a plano-convex lens which has a radius of curvature of

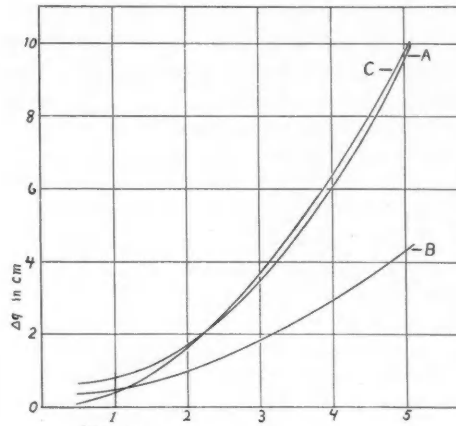

Fig. 2. Longitudinal spherical aberration Δq as a function of the height h of the ray above the central axis. Curve A, plotted from data taken with the plane side of the lens facing source; curve B, with convex side facing source; curve C, theoretical curve corresponding to A.

8.93 cm, index of refraction of 1.54, and diameter of 11.3 cm. The values of Δq for the theoretical curve C were calculated by substituting the constants of the lens into the thin-lens relation given by T. T. Smith,[1] modified to give the aberration Δq and not the reciprocal aberration $\Delta(1/q)$. In each case the object distance was 69 cm.

[1] National Bur. of Standards Sci. Paper No. 461 (1922), p. 561.

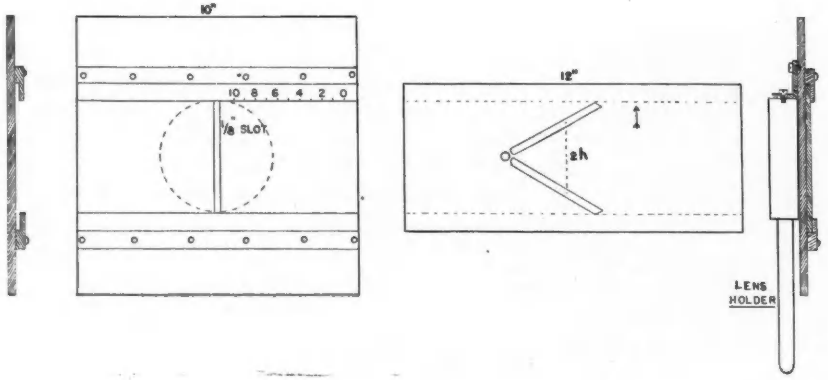

Fig. 1. Details of variable diaphragm.

A Model of Magnetization

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A LECTURE–DEMONSTRATION model containing no iron whatever, but consisting entirely of coils carrying current, illustrates the physical concept of magnetization. Not only do these coils act on one another as small magnets but the elementary magnet itself is thus illustrated by the circulation of electricity representing the orbital motion or spin of the electron.

Fig. 1 is a photograph of the model, one-seventh actual length. A current of 0–20 amp. in the large open solenoid, supplied by a 6-volt battery, furnishes the external magnetizing field in which the 15 small coils, representing atoms of iron, align themselves. These coils are supported above and held below by stout cord. The mechanical torsion which tends to demagnetize the model and return the coils to random angular position, representing the demagnetizing effect of thermal and mechanical agitation, is supplied by light coil springs above and below. These springs serve also as electrical conducting leads. For a current of 1 amp., each coil has a magnetic moment of approximately 200 e.m. units. A brightly colored arrow attached to each coil indicates the direction of the axis.

Fig. 2 shows the coils hanging in random positions controlled by the mechanical suspensions. A mirror attached above the model at an angle of 45° permits this top view to be seen by the class. The mutual effect of the coils, their self-magnetization, is shown in Fig. 3, the current being supplied to the coils by a 30-volt source through rods connected to the center binding posts. Fig. 4 shows the coils aligned in the field of the magnetizing current in the solenoid. The model may be carried slowly through the hysteresis cycle by use of a rheostat and reversing switch in the solenoid circuit, and the retentivity and coercive field noted. In this process the mutual effect of one coil on another is easily observed. The heat loss in transformer iron is illustrated by the kinetic energy of oscillation of the coils, which quickly damps out. The coils have sufficient inertia not to follow rapid reversal of the magnetizing field and they then illustrate the reduced permeability of iron at high frequencies.

The model operates also on alternating current since reversal of current in both solenoid and small coils leaves the direction of torque on the latter unchanged.

Ewing's model of small magnets may be inserted in the solenoid (on d.c.) along with the small coils and put through its hysteresis cycle.

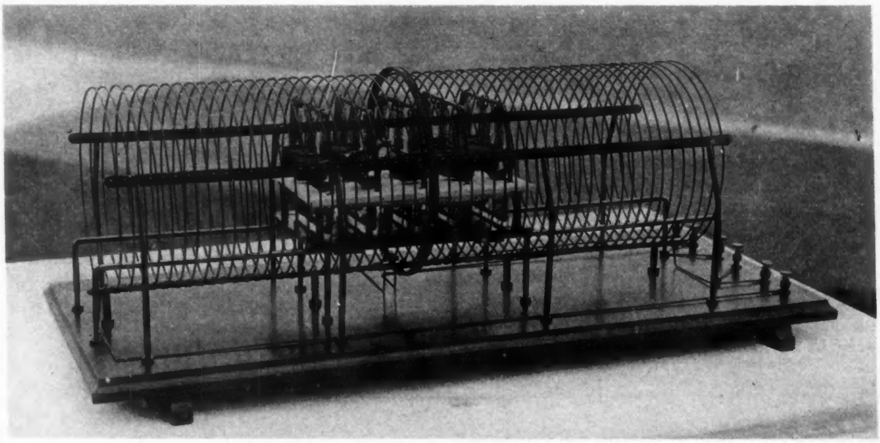

FIG. 1. The model consists of a long open coil with small coils inside, and an external, secondary "test" coil.

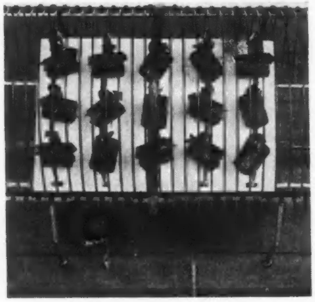

FIG. 2. Top view. Small coils orientated at random.

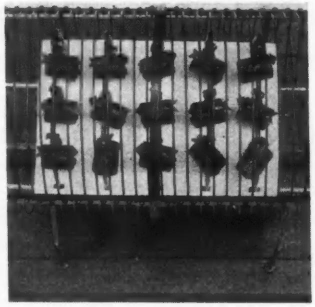

FIG. 3. Small coils containing current and partially aligned by their mutual torques.

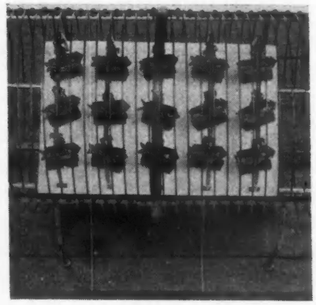

FIG. 4. Small coils aligned in field of solenoid.

The secondary "test" coil wound around the center of the solenoid may be connected to a ballistic galvanometer to show the change in flux and in flux density H_0 with the small coils removed (or carrying no current). With the small coils replaced and carrying current it will show the change in flux density B including the contribution of these coils. With only these 15 model "atoms" the effective permeability is about 1.2 while that of the Ewing model is about 1.1. These effective permeabilities would be greater if the secondary "test" coil did not average over an area considerably larger than that corresponding to the "atoms." With many model "atoms" filling an endless solenoid the effect would be still greater and then the permeability given by the ratio B/H, as measured by the ballistic galvanometer, would correspond to the tabulated values of permeability.

The model illustrates the simplicity gained by using a three-dimensional system of units. In the eyes of the beginner the field of any one of the small coils in exerting torque on the others is not one whit different in nature from the magnetizing field H_0 of the solenoid. The average field of the 15 coils, H_I, simply is added to H_0 to give the total field or flux density B. But consider now the description in a four-dimensional system of units. The applied field $H_0=20$ oersted, at a current of about 20 amp., is found from the ballistic galvanometer deflection of 10 cm by using $B_0=\mu_0H_0=20$ gauss. To be consistent with the electron amperian current explanation of magnetism we are forced to admit an average field of the 15 coils, $H_I=4$ oersted. This is found from $B_I=\mu_0H_I=4$ gauss, computed from the galvanometer deflection of 2 cm when, in the presence of constant H_0, current is introduced in the small coils. Then the total field averaged over the cross section is $H_T=24$ oersted, found from $B=\mu_0H_T=24$ gauss. B is computed from the galvanometer deflection of 12 cm, which either is obtained by adding the deflection of 10 cm for the solenoid and 2 cm for the model "atoms" or is experimentally observed when closing the solenoid and small coil circuits simultaneously. Such numerical duplication of gausses and oersteds is redundant, yet it is not trivial when one insists that B and H are not of the same nature. It seems much simpler to deny any physical meaning to μ_0 and to omit μ_0 altogether as in the three-dimensional systems. Then field and flux density are synonymous terms applying both to H and to B, H_0 being the externally controlled part of B.

When one wishes to press further the analogy of the model to the iron atoms, he may observe that like all models this one illustrates fairly well some aspects of the phenomena under consideration but is weak on other points. An imperfection lies in the distribution of positively charged copper nuclei along the path of the current in the wire of each small coil so that electrostatic effects cancel; whereas the positive nucleus of the real atom is believed to be more nearly concentrated at the center of the atom, with the electrostatic forces of orbital electrons assisting in orienting orbital motion or spin of neighboring electrons as described in modern theory by use of exchange integrals.

COMPARED to the inner satisfaction over a problem successfully solved, any outside recognition becomes meaningless.—RÖNTGEN

Easily Constructed Fresnel Mirrors

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THE Fresnel mirror system here described has the disadvantage that the angle between the reflecting surfaces cannot be varied at will, but the compensating advantage that the only adjustment necessary is to set up the slit at a suitable distance and rotate it in azimuth till the fringes appear.

The angle between the reflecting planes should be of the order of 10′. It is also necessary that the line in which these planes meet shall be nearly parallel and close to the adjacent edges of the two mirrors; that is, the edges must nearly coincide. It is not necessary, however, that the mirrors be optical flats. Plate glass is good enough, and possibly selected pieces of even lower-grade glass would function satisfactorily. The author put together two blocks of plate-glass, each about 1 in. square, broken out of a larger piece, so that they showed the Fresnel fringes in white light quite as well as a more elaborate set with mirrors of black optical glass. The edges were rough, though approximately straight.

The plates were properly oriented and fastened permanently together by a procedure illustrated in Fig. 1. A large piece of plate glass *AB* serves temporarily as a plane base. A strip of good-quality writing paper is laid on this base. Its width *CD* must be a little less than the combined width of the two mirrors. *EF* is a much narrower strip, say 5 mm, of "onion skin" paper, the kind used by stenographers for making letter-copies. *G* and *H* are the two plate-glass squares that are to function as the mirrors, with the better faces downward. The paper strip *EF* is carefully centered on the wider strip *CD*, and the contiguous edges of the mirrors are lined up as nearly over the center of *EF* as possible. A large drop of sealing-wax is fused on the back of each mirror. When everything is set in place, a strip of metal *KL*, about $1/8\times1\times2$ in., is heated till it will melt the wax, carefully laid across the mirrors and allowed to cool. The metal, with the two mirrors fastened in place, can then be lifted off, set up with the reflecting planes vertical and illuminated from a vertical slit set 10–20 cm away from the midpoint of the mirror system. If the fringes are to be cast upon a paper screen, a very bright source of light is necessary. A carbon arc is commonly used, with a condenser lens to condense the light from the positive carbon on the slit.

It is best to have the light fall upon the mirrors at almost glancing incidence, for three reasons: first, the percentage of light reflected is then so large that it makes little difference whether the mirrors are silvered or not; second, at very large angles of incidence faulty mirrors function almost as well as optically perfect ones; third, with this arrangement internal reflections are less likely to cause trouble.

Fringes in monochromatic light are too faint to be shown on a screen, but the mirror-pair can very well be mounted upon the table of a spectrometer and illuminated with monochromatic light through the collimator. Then if the objective of the telescope is removed, leaving only the tube, eyepiece and cross-hairs, monochromatic fringes can be seen readily and their spacing at the cross-hairs measured.

Some difficulty is met in knocking small squares out of a sheet of plate-glass. The following method works rather well. In Fig. 2, *AB* represents the section of a board with a raised edge *C*. The plate of glass is laid on *AB*, and pressed against *C*. A strip of wood *E*, slightly narrower than the dimensions of the desired glass square, also is pressed against *C* and a

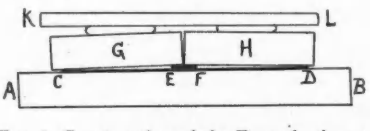

Fig. 1. Construction of the Fresnel mirrors.

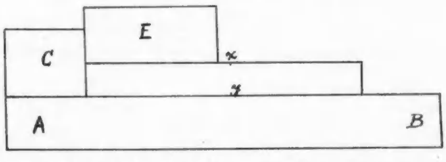

Fig. 2. Method for obtaining small plate-glass squares.

scratch is made at x clear across the plate with a common glass-cutter of the roller type. The plate is then turned over and another scratch y made on the opposite face. These two scratches must be parallel and directly opposite each other. Then the plate is "bridged," so that it is supported at the end and also farther away on the opposite side of the scratches. A sharp blow with a raw-hide or wooden mallet causes the break, which usually follows the scratches rather closely. The strip of glass so secured is cut into smaller pieces by the same method.

Recent Publications

The Nature of Physical Thought. P. W. Bridgman, Hollis professor of mathematics and natural philosophy, Harvard University. 138 p., 14×22 cm. *Princeton Univ. Press*, $2.

Modern physics has created an acute need for a critical analysis of physical concepts and theories. Although a large part of this work must be done by physicists rather than left to philosophers, few physicists are capable or willing to undertake it. The appearance of the present volume by a distinguished physicist of proven ability as a critic and writer is therefore an event of considerable importance.

The book, which is an elaboration of three Vanuxem lectures given at Princeton University in December 1935, contains a wealth of illuminating and thought-provoking observations. It should be read by everyone interested in physical science and certainly by all teachers of physics. An idea of its scope may be gathered from the following chapter headings: Operations, Thought and language, Logic, Mathematics, Mathematics in application, Relativity, Mathematical models and probability, Wave mechanics. While Professor Bridgman's general outlook is akin to that of the Vienna group of logicians, his book has a refreshing vital quality not always found in the writings of the technical epistemologists. Chief among the principles upon which he bases his analysis is the demand, more fully discussed in his previous book, *The Logic of Modern Physics*, that all physical concepts be defined in terms of actual physical operations.

After a brief discussion of the functions and limitations of thought and language, the extravagant claims often made for logic are criticized. The fundamental difference between induction and deduction, only the latter being a truly logical process, is pointed out; and the fact is stressed that a general law of nature, although it may be disproved by a single observation, can never be fully verified.

Mathematics is recognized as being just as truly an empirical science as physics and chemistry. The importance of the text accompanying the mathematical equations of physics is emphasized and the common practice of suppressing it condemned.

The chapter on relativity is one of the most important in the book. After taking the general theory of relativity to task for its uncritical acceptance of many tradition a modes of thought, the author ventures the prediction that "the arguments which have led up to the theory and the whole state of mind of most physicists with regard to it may some day become one of the puzzles of history."

A very apt and delightful discussion is given of probability. While the author's criticism of the fantastic extrapolations of many cosmologists appears justified, his fear that when truth is divested of uniqueness we shall have a flood of "possible" theories seems exaggerated; for, the number of theories will always be effectively limited by the demand that they be comprehensive.

Although the chapter on wave mechanics contains many interesting and instructive remarks, it is less satisfactory to the reviewer than the rest of the book. The gratification which the author derives from the analogy between the quantum-mechanical uncertainties and ordinary errors of observation and several of his other aguments seem not well founded. More serious is the lack of adequate consideration of the critical work of Bohr and Heisenberg.

The absolute soberness of Professor Bridgman gives him an unfailing sense of proportion. This is revealed not least clearly in his repeated assertion that, all success of science notwithstanding, the future is fundamentally unpredictable.

J. Rud Nielsen

History and Biography

Portraits of Eminent Mathematicians, with Brief Biographical Sketches. David Eugene Smith, professor emeritus of mathematics, Columbia University. *Scripta Mathematica* (562 West 144th St., New York), $3.00. Twelve fine reproductions of portraits of Archimedes, Copernicus, Viete, Galileo, Napier, Descartes, Newton, Leibniz, Lagrange, Gauss, Lobachevsky and Sylvester—carefully selected by Professor Smith from his collection of three thousand portraits of mathematicians (and physicists) now in the Library of Columbia University. Each portrait is loosely slipped into a beautifully printed folder containing a biographical sketch. The pictures are 25×35 cm and are admirably suited to framing.

If Davy had not been the first chemist, he would have been the first poet of his age.

—Coleridge

DISCUSSION AND CORRESPONDENCE

Acceleration Calculations from Spark Recorded Data

I AM much interested in the conclusion of E. M. Pugh [Am. Phys. Teacher 4, 70 (1936)] that it is worth while to use a least-squares solution in determining acceleration from a spark record. It may be of some further interest in this connection to remark that the least-squares formula of the article cited may be cast in a form which makes the acceleration depend upon a weighted mean of second differences of the spark-position readings. Thus Pugh's Eq. (2) may be written:

$$a=\Sigma w_i(S_{i+2}-2S_{i+1}+S_i)/T^2\Sigma w_i,$$

where $w_i=w_{n-i-1}=i(i+1)(n-i-1)(n-i)$,

and $\Sigma w_i=(n-2)(n-1)n(n+1)(n+2)/30$,

the summations extending from $i=1$ to $i=n-2$. This use of the second differences will have a certain reasonableness for the student quite apart from any understanding of least squares. Moreover, if the second differences have already been computed for pedagogical reasons or as a test of the data, it allows some saving of computational labor in that usually the first significant figure in all the second differences will be the same and need not be involved in the averaging process.

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Textbook Discussions on Lightning

SINCE the dawn of civilization, the phenomena connected with the lightning discharge have attracted the attention of mankind, both because of the magnificence of these electrical displays and because of the ever present factor of danger to life and property to which they may give rise. One would expect, therefore, that every textbook in general physics should devote several paragraphs to the thunderstorm and its attendant phenomena. It would also be logical to anticipate that writers in the United States should give some attention to Benjamin Franklin's kite experiment, and to the use of the lightning rod which resulted from his investigations.

A careful survey of sixteen recent college textbooks in general physics reveals the fact that this whole subject is omitted entirely by five; that the statements regarding the formation of charges in the clouds, and the nature and prevailing sign of the discharge, is wrong in four of the sixteen; and that in three others the treatment is elementary and avoids any discussion of the sign, origin and distribution of the charge in the cloud. In only four of the books examined are found statements that are adequate and in conformity with recent investigations in this field. One text with a 1936 copyright states that "A thundercloud is positively charged and induces negative charges on the earth and in the atmosphere near the earth," thus leading the student to the erroneous conclusion that clouds always carry positive charges while the charges near the earth are always negative.

As the result of extensive researches in atmospheric electricity published within the last ten years, two things may be considered as definitely settled. In the first place, the investigations of Schonland in South Africa, Banerji in India, Lewis and Foust, and the writer in America, and many others, have established the fact that most of the discharges which strike the earth carry negative electricity from the cloud to ground, and that branching may proceed from a seat of negative as well as from a seat of positive charge. Secondly, the typical multiple discharge consists of two parts. The first is a pilot spark of negative electrons from the cloud to earth. This forms an ionized path over which surges of positive ions from the earth and lower atmosphere rush upwards to neutralize the negative space charge of the cloud. The latter may also descend, under certain conditions, to meet the uprush of positive ions. In either case the resulting change in the potential gradient between cloud and earth would be the same. Details are given in the publications of Schonland and of Halliday in South Africa, and of McClernon and his colleagues at the Westinghouse Laboratories in Pittsfield, Massachusetts.

Furthermore, to the moot question of the objective reality of ball lightning has been brought the evidence of a series of actual photographs of the phenomenon, and some progress has been made towards a satisfactory explanation of its cause.

For the benefit of those interested, the following brief bibliography is given. More complete references will be found in the articles cited.

Monographs:

B. F. J. Schonland, *Atmospheric Electricity* (Dutton, 1932).

Paul G. Guest, *Static Electricity in Nature and Industry*, Bull. 368, U. S. Bureau of Mines (Government Printing Office, Washington, 1933).

M. E. Mathias, *La Foudre et sa forme globulaire*, Memorial de L'Office National Meteorologique de France (Rue de L'Université, 196, Paris, 1935).

Articles:

S. K. Banerji, "The Electric Field of Overhead Thunderstorms," Phil. Trans., Roy. Soc. London, A **231**, 1–27 (1932); also J. Roy. Meteor. Soc. **56**, 305–335 (1930).

W. W. Lewis and C. M. Foust, "Direct Strokes to Transmission Lines," Gen. Elec. Rev. **34**, 452–458 (1931).

J. C. Jensen, "The Branching of Lightning and the Polarity of Thunderclouds," J. Frank. Inst. **216**, 707–748 (1933); "Ball Lightning," Physics **4**, 373–375 (1933), and Sci. Mo. **37**, 190–192 (1933).

B. F. J. Schonland, D. J. Malan and H. Collens, "Progressive Lightning," Proc. Roy. Soc. **A152**, 595–625 (1935).

B. F. J. Schonland, "The Development of the Lightning Discharge," Trans. S. A. I. E. E. **24**, 145–152 (1933).

K. B. McEachron, W. L. Loyd and W. A. McMorris, "Lightning Strikes Twice," Gen. Elec. Rev. **37**, 350–351 (1934).

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Laboratory Experiments on the Viscosity of Air—An Undergraduate Project

VARIOUS methods for determining the coefficient of viscosity η of air were studied with the object of developing a suitable apparatus and experiment for the elementary or intermediate laboratory. Such an experiment along with one on the density of air provides all the data needed to calculate mean speeds and mean free paths of air molecules.

The capillary-tube method was found to be the most suitable; the apparatus is easy to construct and the relatively simple theory includes Poiseuille's formula for liquids as a special case. The apparatus finally adopted (Fig. 1) is a slightly modified form of A. O. Rankine's simple U-tube arrangement.[1] The glass U-tube is not more than 3.5 mm inside diameter and its limbs are 35 and 10 cm long. A glass bulb with a side opening is sealed to the longer limb. Rubber pressure tubing connects the shorter limb to a piece of thermometer tubing 20 cm long and not more than 0.2 mm internal diameter. The glass must be clean and the ends of the capillary tube must not be touched. The tubes and a scale are mounted on a vertical board which is pivoted near the center (Fig. 1).

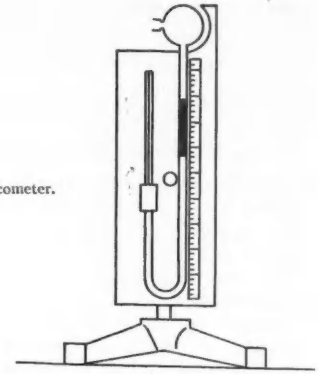

FIG. 1. Simple U-tube viscometer.

The apparatus first is rotated 90° clockwise and enough clean mercury is poured into the bulb to form a pellet about 8 cm long in the long limb. It is next returned to the vertical position and the time the pellet takes to descend some measured distance in the fall-tube is observed. The apparatus is then inverted by turning it clockwise and the time for the pellet to return a measured distance is found. This is repeated several times to obtain average times of fall and of return and then the whole procedure is repeated with at least two other, shorter pellets of known length. The mean diameter of the capillary tube is found by weighing on an analytical balance, to two significant figures at least, the thread of pure mercury that fills a measured length of the tube; this obviously is a difficult determination and ordinarily should be made once and for all and marked on the tube. The radius of the fall tube can be found by the student in a similar manner. Other data needed are the length of the capillary tube, the barometric pressure and the temperature.

For a given capillary tube, our values for η differ from the mean by less than 2 percent. The mean values obtained with different tubes differ as much as 2 percent. The results of all our runs place η for atmospheric air, 20°C, at 183 ± 3 μpoise. A correction of about 4 percent was made for the surface tension effect in the mercury pellet; since 10 or more runs with different pellets are needed for this correction when only ordinary precautions are taken to keep the glass and mercury clean, it is best to omit it in a student experiment. Corrections for the end-effect and for the slip between the gas and the walls of the capillary tube were found to fall within the experimental error. This experiment is being used successfully in the freshman course at the California Institute of Technology.

A second type of capillary-tube apparatus investigated is essentially a constant-volume gas thermometer, with a capillary tube sealed to the thermometer bulb.[2] It gave values for η which agree, within the experimental error, with those obtained with the U-tube apparatus. No correction for surface tension effects is required, the end-effect is negligible and gases other than air can be tested. Considerable practice in manipulation is needed to obtain consistent results and the theory cannot be developed easily without the aid of the calculus.

Because of the difficulty of determining the diameter of a capillary tube of very small bore, an attempt was made to devise a large-scale apparatus for use with a 1-mm tube. The apparatus consisted of three thin-walled iron cylinders of diameters 8, 10 and 12 cm respectively, and height 15 cm. The smallest and largest cylinders were welded to a solid iron base and the space between them filled with mercury. The remaining cylinder, which was closed at the top, was forced down into the mercury by weights, thus driving air out through the capillary tube attached to it. Unfortunately, this method is complicated by necessary corrections for buoyancy, surface tension and a large end-effect. Moreover, friction between the mercury and iron, and between the iron parts, produces errors of 6–12 percent that depend upon the speed of the movable cylinder.

Two other standard ways of investigating gas viscosity are the method of torsional oscillations and the constant-deflection method. The first of these, which involves observations of the damping of the oscillations of a disk suspended in the gas, is not suitable for beginners because of mathematical difficulties and an elaborate, lengthy technic. The constant-deflection method, in which the gas is contained between parallel disks or coaxial cylinders, is also unsuitable, for it is difficult to design an apparatus for gases that will be rugged, easy to adjust and inexpensive.

The experimental part of this work was done by the junior author while he was a senior and a second-year student in physics.

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[1] For the theory see: Newman and Searle, *The General Properties of Matter* (1929), p. 211; Edser, *General Physics for Students* (1932), p. 517; etc.

[2] A. Anderson, Phil. Mag. **42**, 1022 (1921); Newman and Searle, ibid., p. 212; Worsnop and Flint, *Advanced Practical Physics for Students* (1923), p. 174.

DIGEST OF PERIODICAL LITERATURE

Apparatus and Laboratory Practice

Adjustable support and stand for Bunsen burner. I. A. Balinkin; *J. Chem. Ed.* **13**, 414, Sept., 1936. The device shown in Fig. 1(*a*) is useful for supporting vessels or objects to be heated on a crowded laboratory table. By adjusting the heights of the split piece of brass A and the rod B, the 4-in. ring C can be brought either close to or as high as 6 in. from the mouth of the burner. The device may also be used as in Fig. 1 (*b*) to support a burner at the spectroscope slit in flame spectra experiments.

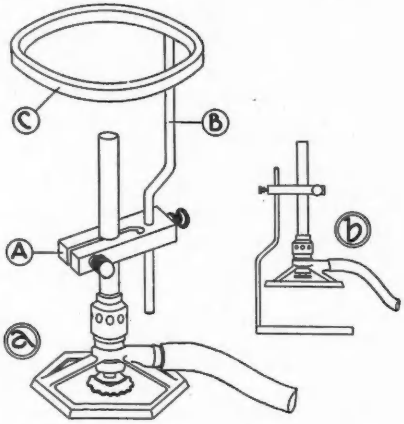

Fig. 1. Support and stand for Bunsen burner.

Increasing the swing of a ballistic galvanometer. W. B. Ellwood; *Bell Lab. Rec.* **13**, 150–5 (1935). The ballistic galvanometer is frequently used to measure the response of a magnetizable material to a magnetizing force. In one form of measurement the material is made the core of the magnetizing coil and is subject to the force due to a reversal of the magnetizing current. The amount of induced magnetism is detected by a test coil wound on the same core and connected to the galvanometer.

When the magnetizing forces are very small and the quantity of electricity delivered to the ballistic galvanometer correspondingly small, precise measurements are difficult or impossible. Such measurements of magnetic materials are very important in Bell Telephone Laboratories, however, because telephonic currents are small and their several components (of various frequencies) even more minute. The technic devised there for building up an accurately measurable swing of the galvanometer might also be of interest in college laboratories. It makes use of the principle that a small force repeatedly applied at proper intervals can produce vibrations of large amplitude. In Fig. 1, every time the galvanometer coil swings through its zero position, the beam of light passing from the galvanometer to the scale strikes a photoelectric cell. The current from this cell acts through a relay to reverse the current in the primary winding of the transformer under test, and thus passes another pulse of electricity through the galvanometer in a direction tending to increase its swing. There is a limit, of course, to the possible amplitude and that depends for any galvanometer system upon the quantity of electricity delivered at each reversal. This maximum amplitude is reached after about 100 swings in the apparatus described. To eliminate the damping effect of the air the moving coil of the galvanometer is suspended in a vacuum for which the mean free path of the gas molecules is larger than the diameter of the coil.

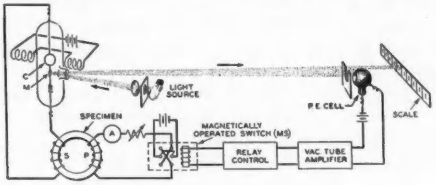

Fig. 1. Diagram of apparatus.

General Physics

Derivation of the equation $pv = RT$. L. McCulloch; *J. Chem. Ed.* **13**, 393–4 (1936). In a book review in J. Phys. Chem. **33**, 1118 (1929), W. D. Bancroft asks: "Why should not the student be shown how to combine $v=KT$ and $p=kT$ so as to get $pv=RT$? The most obvious way of combining them gives $pv=RT^2$, which we know is not right." This question brings to mind the following method of derivation.

Commence with the two experimental relations for a gas,

$$v=KT(p\text{ constant}),\quad p=kT(v\text{ constant}),\tag{1}$$

which are to be combined into one equation that connects the variables p, v, T. Since K and k are functions of p and v, respectively, Eqs. (1) may be written:

$$v=F(p)T,\quad p=f(v)T.\tag{2}$$

Forms must now be found for these functions such that Eqs. (2) are simultaneously true.

Treat p and v as independent, with T dependent for its value upon them. Then consider Eqs. (2) as simultaneously true and combine them by eliminating T; thus

$$vf(v)=pF(p).\tag{3}$$

Each member of Eq. (3) contains only one variable and, since p and v are independent, the members must vary

independently, if at all. But the two members of an equation cannot vary independently. Hence they must have a constant value, say R. Thus the required forms of the two functions are $f(v)=R/v$ and $F(p)=R/p$. Substituting in Eq. (2), we obtain, finally, $pv=RT$.

For a discussion of other derivations of the equation, see Roseman and Katzoff, J. Chem. Ed. **11**, 350 (1934), or the digest in Am. Phys. Teacher **2**, 127 (1934).

Report of the commission of symbols, units and nomenclature of the International Union of Pure and Applied Physics. E. G.; *Nature* **135**, 419–20 (1935). Among the recommendations are the following with respect to thermal units and thermodynamic symbols: (1) The unit of heat when measured in units of energy shall be the *joule*, defined as equivalent to 10^7 ergs; (2) The *gram-calory* is the amount of heat required to raise the temperature of 1 g of water from 14.5° to 15.5° of the International Scale of Temperature under standard atmospheric pressure; (3) Symbols to be used are S for entropy, U for internal energy, F for free energy, G for thermal potential (Gibbs function), H for heat content (enthalphy), and W for work; E, φ and I are to be accepted as alternative symbols for internal energy, entropy and heat content, respectively; (4) Thermodynamic quantities should always be expressed in the centigrade system.

Future activities of the Commission will include cooperation with international bodies in the preparation of lists of definitions and of lists of terms that occur in two or more branches of physics. Assistance will be given to those who are engaged in preparing such lists, with the view of bringing workers in different countries into contact and securing harmony in the results of their work.

Science Education

Teaching science for the purpose of influencing behavior. V. H. Noll; *Sci. Ed.* **20**, 17–20, Feb., 1936. (1) Desired attitudes which are to influence behavior must be taught directly. (2) The scientific attitude can be developed only by giving students the opportunity to practice it. (3) If any attitude is to function in everyday life, specific provision for generalizing it must be made in our teaching. (4) The scientific attitude and habits of scientific thinking must be made desirable objectives if they are to be truly acquired by students.

General Education

Knowledge *versus* thinking. B. D. Wood and F. S. Beers; *Teachers Coll. Rec.* **37**, 487–99, Mar., 1936. Without knowledge and facts there can be no thinking. Those who prefer thinkers unfettered by facts display a fear of rote memory and a suspicion of anything that even suggests that remembering is not a criminal act. Teachers cannot create thinkers. The assertion that the purpose of the social studies is to teach students to apply the principles and generalizations of these studies to new social problems, or to deal with the problems of a changing civilization, seems to be an excellent example of an empty generalization. Teachers of the social studies as a group do not appear to be notably distinguishable from other teaching groups in regard to citizenship; they are not ordinarily regarded as better citizens, as more unselfish in economic or social conduct, as more intelligent voters, or as affording more or better social leadership than other teaching groups.

Miscellaneous

The creative years. H. C. Lehman; *Sci. Mo.* **43**, 151–62, Aug., 1936. To obtain some definite information on the question of what years in man's life are the most creative, the author, a psychologist, has compiled information on the ages at which contributions were made in several scientific and other fields (Table I). Fig. 1 is based on 141

Table I. *Summary of main findings.*

Field	No. of workers	No. of works	Median age	Mean age	Stand. dev.	Yrs. of max. output
Chemistry	244	993	36	38	10	28–32
Mathematics	163	453	38	41	14	34–38
Physics	90	141	38	39	11	30–34
Astronomy	63	83	44	45	12	43–47
Invention	402	554	35	37	11	31–35
Short story writing	220	1,396	38	41	12	33–37
Poetry	82	797	33	38	16	26–30

contributions of 90 physicists included in Magie's *A Source Book of Physics*. Averages were taken as indicated in order to make allowance for the unequal numbers of individuals alive at the various age levels.

Although some variation exists in the shapes of the curves for the various fields and in the precise age levels at which the curves reach their maximums, nevertheless, for most of the fields studied by the author, the curves reach their peaks at a relatively youthful age and they *fall off rapidly* after passing the peaks. School books usually picture the renowned scientist as a man of rather advanced years, probably partly because personal fame spreads slowly; but apparently the typical outstanding scientist really is in his late twenties or his thirties at the time of his important creative work.

The rapid drops in productivity of the scientists at relatively early ages might be explained by saying that it is the gifted scientists who are most often drafted for time- and energy-consuming administrative and classroom

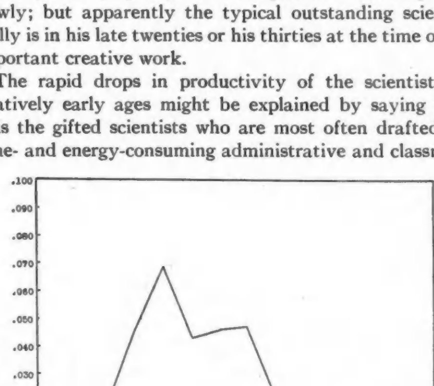

Fig. 1. Average number of contributions made by physicists during each year of their lives.

duties, were it not for the fact that the curves for inventors, poets and short story writers show the same characteristics. Even Edison, who was very active throughout a period of 60 years, was most productive at 35; he took out more than a fourth of all his patents between the ages of 33 and 36. Moreover, when the relative importance and significance of contributions are taken into account, it also becomes apparent that the drops in the curves beyond their peaks cannot be attributed to the idea that the older scientists are more discriminating and disdain to publish findings of minor importance. In chemistry, for example, the most significant contributions were made most frequently at 30 years of age.

Large individual differences exist, of course. Some persons do their best work when they are relatively old. If an individual has failed to make a contribution by the time he is 40, it would of course be quite erroneous to assume that he will never make one. It must also be remembered that the foregoing data do not indicate the relative creativity of men of different chronological ages. Nor is the inference to be drawn that the decreased research productivity of the older scientists necessarily means that their scientific and social usefulness in many other directions also decreases. Some of the older men may make their later contributions *through their students;* there probably is such a thing as "creative teaching" and this may be fully as important to society as is that which is customarily referred to as scientific productivity. The data for inventors, poets and certain other groups indicate, however, that considerations such as these do not serve to explain why the curves for research productivity wane so noticeably after an early age.

It is not believed that the decrements in creativity at the older ages imply a corresponding decrement in the ability to create. Outstanding potential ability probably is present in the individual who makes original and noteworthy contributions in any field. But potential ability alone does not gurantee accomplishments. Genius probably is not solely the fruit of any single trait but depends upon the fortunate combination of various personal traits and environmental conditions. At the older ages, some one or more of the numerous variables that are essential to the fruition of genius apparently tend to wane or to disappear.

The original article contains additional data and many details. It might be of interest to compile age-curves for experimental and theoretical physics considered separately.

Teaching Aids

Motion Picture Films

Glass Insulators. Silent, 16 mm, 23 min., 2 reels. **Glass Containers.** Silent, 16 mm, 45 min., 3 reels. *Whitall Tatum Co.* (225 Varick St., New York), gratis except for return transportation charge. The films show in detail the operations from the mining of the sand to the fabrication of the finished glassware.

Carbon Knock in the Modern Motor. Sound, 16 and 35 mm, 30 min., *Union Oil Co. of California* (Los Angeles), lent gratis. Animated explanation of the principles of the internal combustion engine and of the effects of carbon deposition in cylinders.

Catalog of Motion Pictures. *International Educational Pictures* (1430 Massachusetts Ave., Cambridge, Mass.), gratis. Contains a list of natural science subjects, 19 of which are in physics.

Posters

Chemical Products in the United States. 48×64 cm. *Silver Burdett Co.* (Newark, N. J.), gratis. A two-color outline map of the United States, with chemical products indicated by states.

Pamphlets

The Earth's Magnetism. Daniel L. Hazard, Division of Terrestrial Magnetism, U. S. Coast and Geodetic Survey. 52 p., 23 fig., 15×23 cm. *Government Printing Office* (Washington), 15 cts. An elementary discussion of the early history and fundamental properties of magnets, the nature of the earth's field, the methods and instruments used in the field and in observatories to measure the earth's field, and the theories which have been advanced to account for the earth's magnetism and its variations.

Publications of the U. S. Coast and Geodetic Survey. The Survey maintains a mailing list of persons desiring to receive notices of the issuance of charts and many other publications. Address the Director, U. S. Coast and Geodetic Survey, Dept. of Commerce, Washington.

Outline of the History of Mathematics. Raymond Clare Archibald, professor of mathematics, Brown University, 58 p., 15×23 cm. *Mathematical Association of America* (Oberlin, O.), paper, 50 cts. A reprint of two lectures, given in 1931 at the Summer School for Engineering Teachers of the S. P. E. E. Contains a good bibliography.

Metallurgy and Wheels. 47 p., 14×21 cm. *General Motors Corporation* (Research Lab. Sec., Tech. Data Dept., Detroit, Mich.). A simple account of the part played by metallurgy in automobile manufacturing. Good diagrams. Free from objectionable advertising.

How Glass Bottles are Made. Elizabeth M. Bacon. 15 p., 19 fig., 14×22 cm. *Whitall Tatum Co.* (225 Varick St., New York), gratis. A simple, attractive outline of the history of the art of glass making and of present day methods in "the oldest manufacturing industry in America."

Perspective and Optical Illusions of Depth. Theodore M. Edison. 44 p., 31 fig., 15×23 cm. *Calibron Products* (West Orange, N. J.), 50 cts. A semi-technical discussion of optical illusions of depth, and of perspective methods and problems. Excellent illustrations.

Suggestions for the Use of Polaroid in Demonstrations of Polarized Light. 15 p., 11 fig., 15×23 cm. *Polaroid Corp.* (285 Columbus Ave., Boston), gratis. Describes 18 excellent lecture demonstrations of polarized light that can be made with the "Polaroid Experimental Kit."

Author Index to Volume 4

In this index are listed the names of the authors and the titles of their articles. Abstracts of papers read at the annual meeting and articles that appear in the "Digest of Periodical Literature" section of the journal are not listed; they are indexed in the *Analytic Subject Index.*

Analytic Subject Index to Volume 4

The titles of articles are disregarded, the entries being based on analyses of the contents of the original articles. Entries marked (D) refer to digests appearing under "Digest of Periodical Literature" and to abstracts of papers read at the annual meeting; entries marked (R) refer to reviews appearing under "Recent Publications" and "Teaching Aids."

THERE is no grander nor more intellectually elevating spectacle than that of the utterances of the fundamental investigators in their gigantic power. Possessed as yet of no methods—for these were first created by their labors and are only rendered comprehensible to us by their performances—they grapple with and subjugate the object of their inquiry and imprint upon it the forms of conceptual thought. Those who know the entire course of the development of science will . . . judge more freely and more correctly the significance of any present scientific movement than those who, limited in their views to the age in which their own lives have been spent, contemplate merely the trend of intellectual events at the present moment.—Ernst Mach